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DESIGN STUDY OF ANTENNA GIMBAL SYSTEM FOR LANDSAT-D

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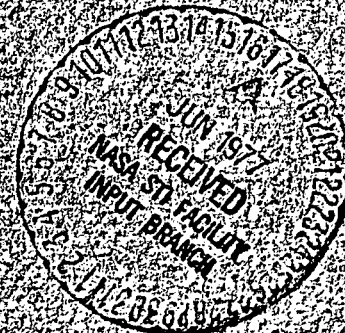
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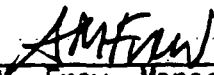
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1.0 INTRODUCTION

This report represents the conceptual design studies of a two-axis antenna drive assembly (ADA) for the TDRSS link communications subsystem for LandSat-D. The configuration of the communications subsystem is based on a study performed by TRW for NASA/GSFC, report No. 14897-6007-RU-00, "Design Study LandSat Follow-on Mission Unique Communications System," Reference # 1. Performance requirements for the subject ADA are derived from an attitude control system (ACS) study performed by TRW for the same application, Reference # 2.

The objectives of this study are to conduct conceptual design studies to derive a recommended ADA configuration and to define its hardware requirements, including drive electronics.

Although a deployment boom will be required to place the antenna and ADA from the stowed position to the deployed position after launch, and to retract them for retrieval, the boom design and deployment mechanism are not a part of this study. For clarification, however, a packaging layout of the steerable antenna, the ADA, and a section of the deployment boom have been generated to ascertain the adequacy of allocated stow space in the nose cone of the launch vehicle, as defined by Grumman Aerospace, Reference # 3.

The study results are summarized in Section 2.0. The gimbal design tradeoff is presented in Section 3.0. The recommended ADA design and its component tradeoffs are discussed in Section 4.0. The drive electronics is described in Section 5.0.

2.0 SUMMARY

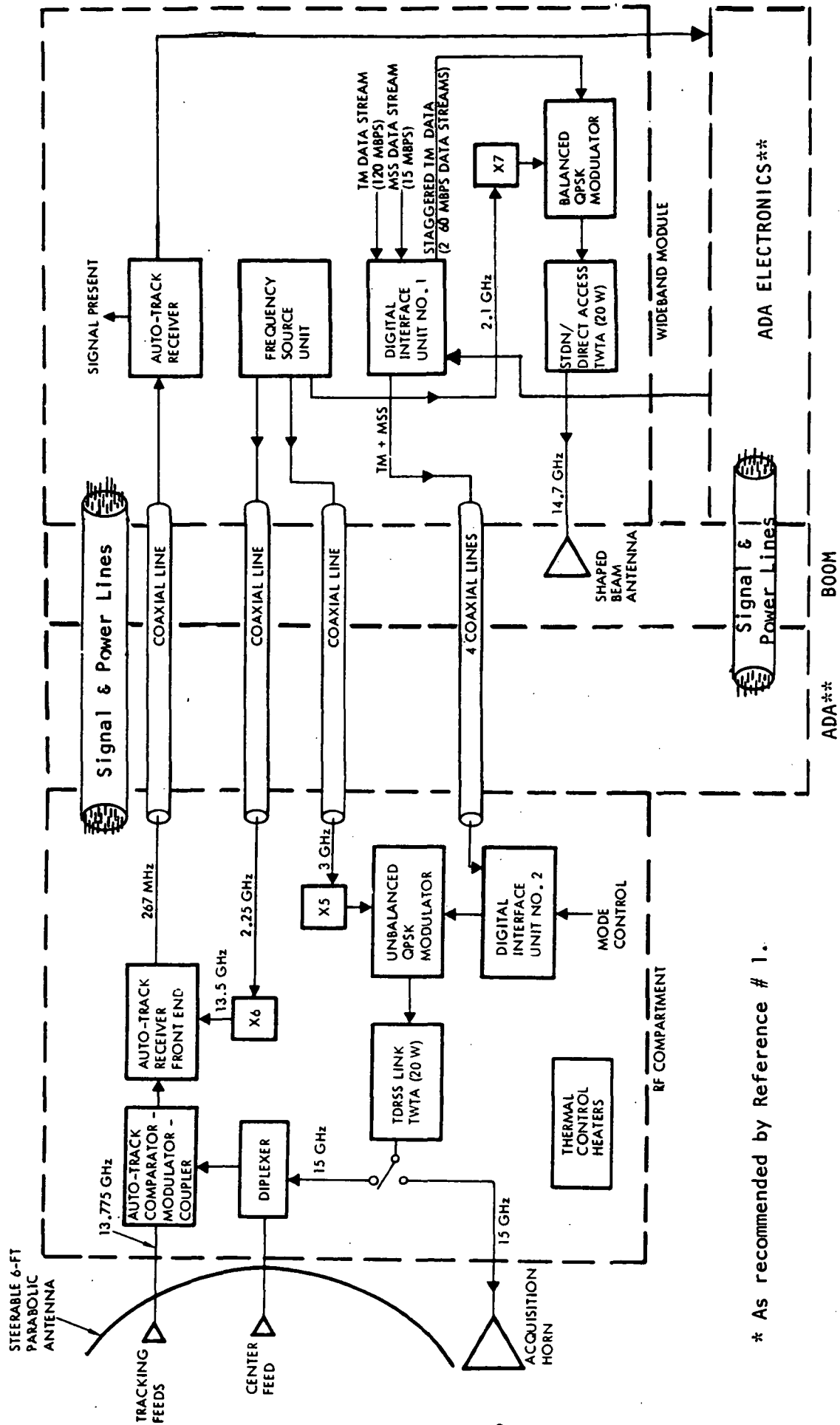
The recommended antenna drive assembly (ADA) is a simple and reliable design substantially similar to the antenna and solar array drives developed and space-qualified by TRW for spacecraft programs such as DSCS II and FltSatCom. (In particular, several of the DSCS II antenna drive assemblies have already accumulated many years of operating life in space without a single failure.)

As prescribed in the communications subsystem design, (shown in Figure 2-1,) the function of the ADA is to steer the 6-ft parabolic antenna and its RF compartment within a spherical sector - greater than a hemisphere - for both acquisition and tracking. Since the wideband module of the communications subsystem is separated from the TDRSS link transmitter and autotrack receiver front end, all the RF cables (3.0 GHz and lower) and other signal and power lines have to be carried across both gimbal axes over a maximum range of $\pm 200^\circ$ rotation. Consequently, a cable wrap assembly has to be developed and incorporated into the ADA.

Figure 2-2 depicts the physical configuration of the ADA. It consists of two (2) identical drive modules mounted in a T-configuration to satisfy the elevation over azimuth requirement. A mechanical schematic, shown in Figure 2-3, illustrates all the components and their relationship in each axis of the ADA.

Each drive module contains a 1.8° stepper motor as the prime mover and a small harmonic drive reducer, which provides a 100:1 gear reduction between the motor and the ADA output shaft. A single speed resolver serves the dual function of providing the control loop error signal and telemetry position information. The gimbal bearings are a duplex pair of angular contact ball bearings preloaded by means of a set of preground spacers. An oil-lubrication system identical to the forementioned proven designs is incorporated into the recommended ADA bearing and gear lubricating scheme.

The cable wrap design required not only configuration investigation, but also the search for a coaxial cable with better flexibility and lower insertion loss than RG-142B or RG-400. The recommended cable wrap design



* As recommended by Reference # 1.

** Subjects of this study.

FIGURE 2-1. COMMUNICATIONS SUBSYSTEM* AND ADA INTERFACE

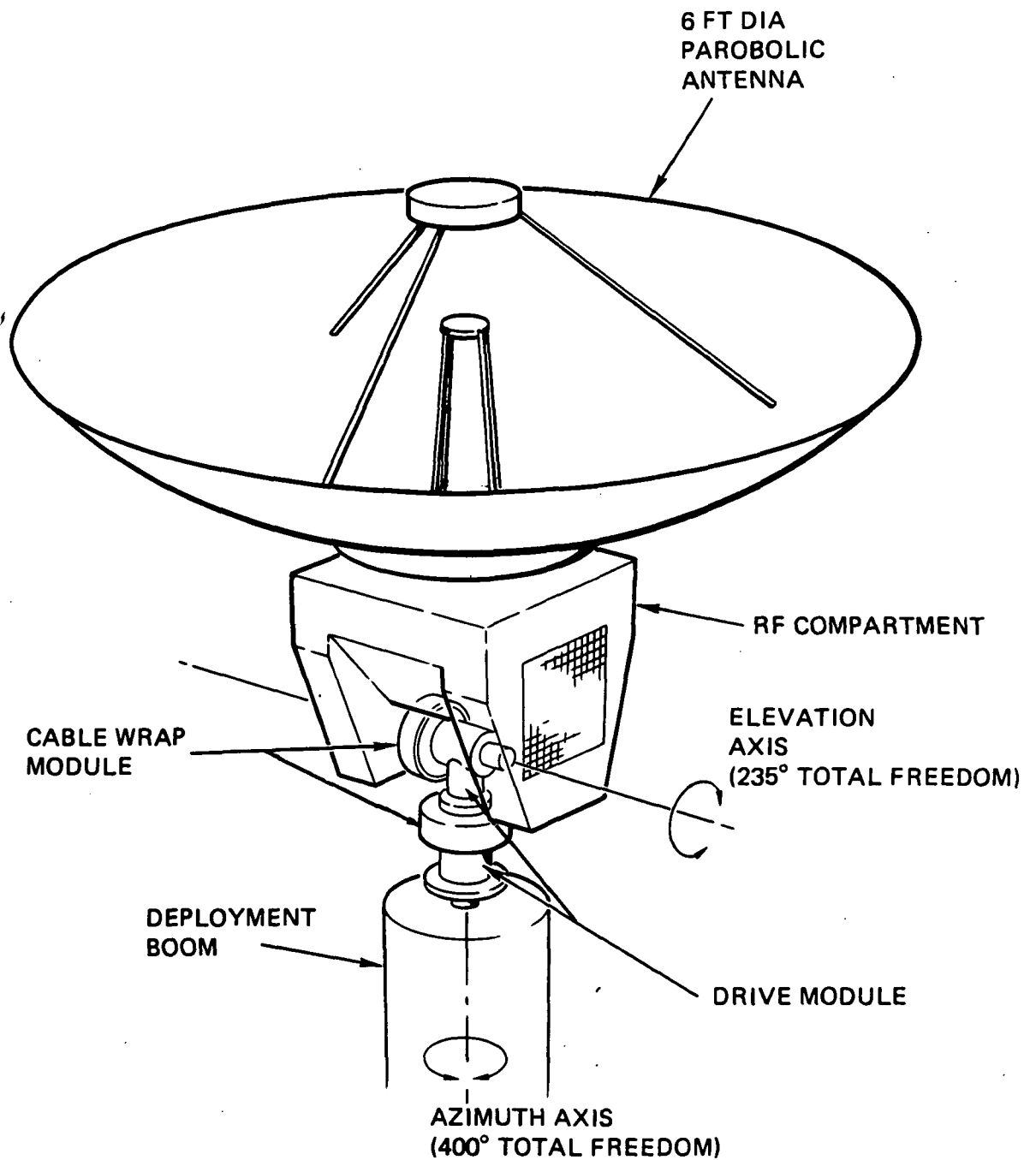


Figure 2.2. Recommended Gimbal Configuration

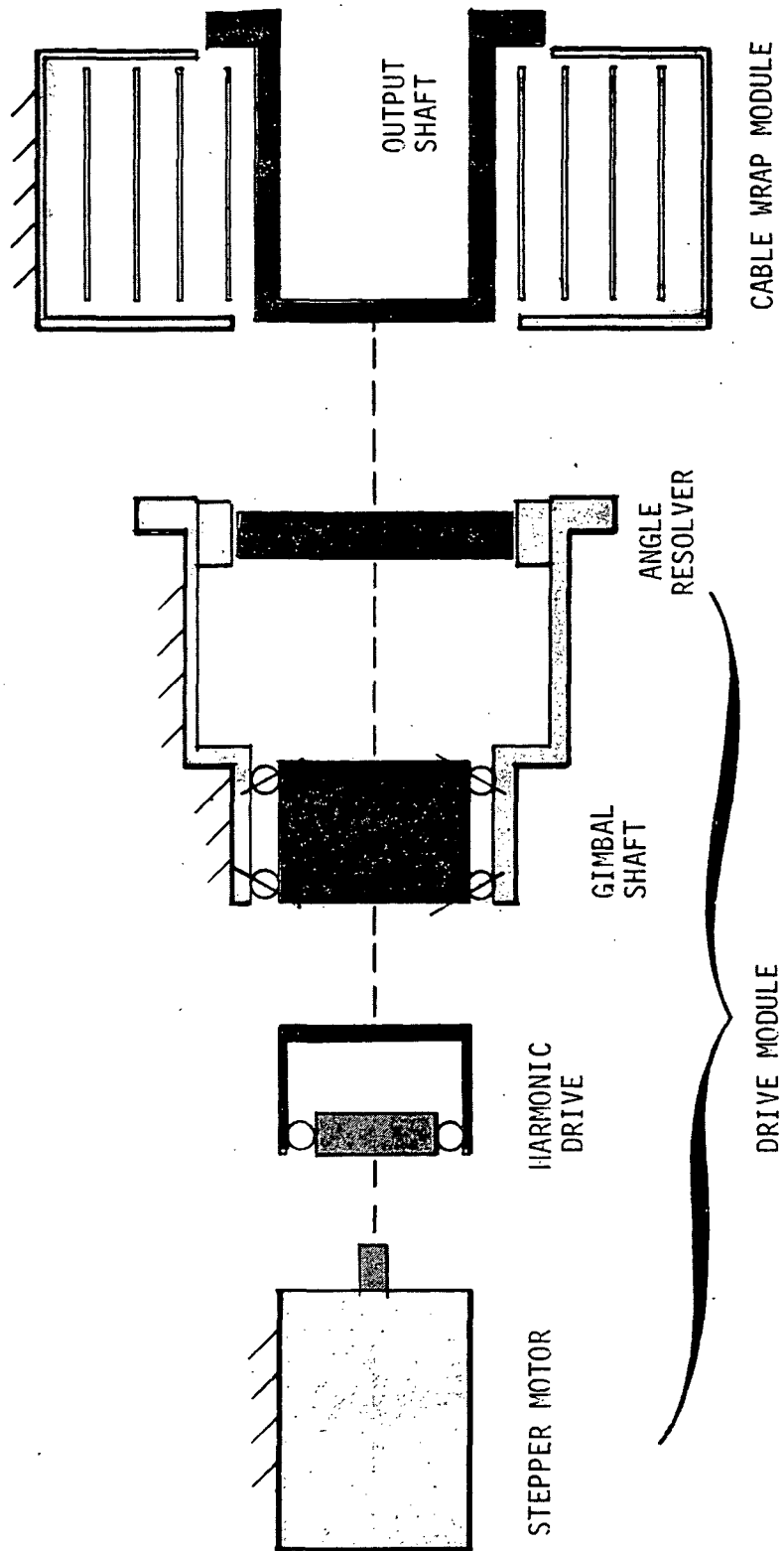


FIGURE 2.3. MECHANICAL SCHEMATIC OF ADA
(SINGLE AXIS)

consists of two flat ribbon cables - one with 31 single shielded wires and the other with 20 shielded pairs - and seven (7) coaxial cables also tied into a flat ribbon configuration. The cable wrap assembly is made into a module which is mounted directly onto the drive module; see Figure 2-3.

For better environmental control, the ADA electronics module is to be mounted in the instrument bay of the spacecraft itself. Each drive module has an external thermal blanket and a thermostatically controlled heater to maintain the cable wrap module temperature above 40°F for lower cable torque and longer cable life. In order to relieve the dynamic launch loads from the gimbal bearings, a simple caging mechanism is recommended to latch the antenna assembly to the deployment boom during launch and retrieval.

The functional block diagram of the ADA and its drive electronics is shown in Figure 2-4. The performance capability and physical characteristics of the ADA are tabulated in Table 2-1.

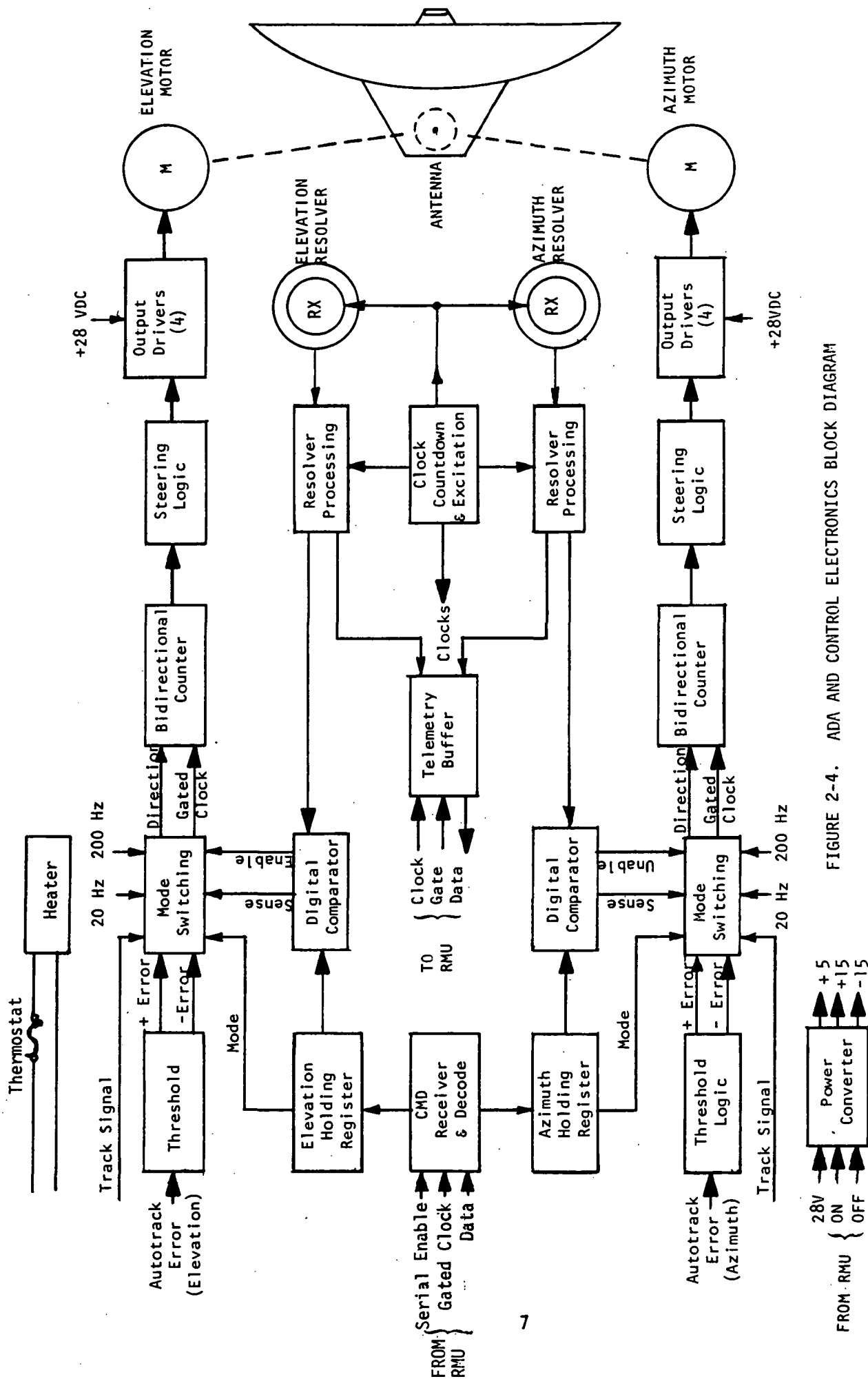


FIGURE 2-4. ADA AND CONTROL ELECTRONICS BLOCK DIAGRAM

TABLE 2-1. PERFORMANCE CAPABILITY AND PHYSICAL CHARACTERISTICS OF RECOMMENDED ADA

GIMBAL CONFIGURATION:	ELEVATION OVER AZIMUTH
ANGULAR FREEDOM:	
ELEVATION -	-28° TO <u>±</u> 208°
AZIMUTH -	<u>±</u> 200°
OUTPUT STEP SIZE:	0.018°
SLEW RATE, MAXIMUM:	4.5°/SEC
POINTING ACCURACY, OPEN LOOP:	0.2°
READOUT ACCURACY:	0.15°
DETENT TORQUE:	37 IN-LB, MINIMUM
POWER:	
SLEW -	10 WATTS/AXIS
TRACK -	<0.5 WATTS/AXIS
ELECTRONICS -	3 WATTS/AXIS (SLEW)
SIZE:	
DRIVE & CABLE MODULE -	7" DIA X 8-3/4" EACH AXIS
ELECTRONICS -	10" X 9" X 3"
WEIGHT:	
DRIVE & CABLE MODULES -	17.5 LBS TOTAL
ELECTRONICS -	6 LBS TOTAL
HEATER:	
TYPE -	THERMOSTATICALLY CONTROLLED STRIP HEATER
POWER -	2-1/2 WATTS, TOTAL
INSULATION::	FORMED MULTIPLE LAYER ALUMINIZED KAPTON
REDUNDANCY:	NONE
CAGING:	EXTERNAL CAGING REQUIRED FOR LAUNCH

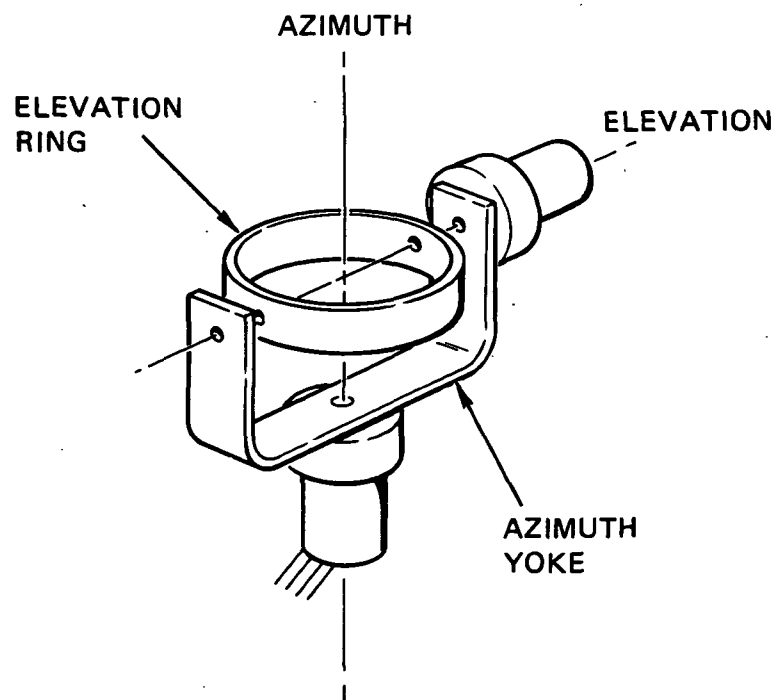
3.0 GIMBAL DESIGN TRADEOFF

For a gimbal configuration of elevation-over-azimuth, the conventional design approach is an elevation gimbal ring supported by an azimuth yoke as shown in Figure 3-1-a. The servo drive components are packaged around each gimbal shaft, and the two gimbals are then integrated together into a single antenna drive unit. Another approach, however, is to utilize two identical drive modules for the desired axis orientation, shown in Figure 3-1-b.

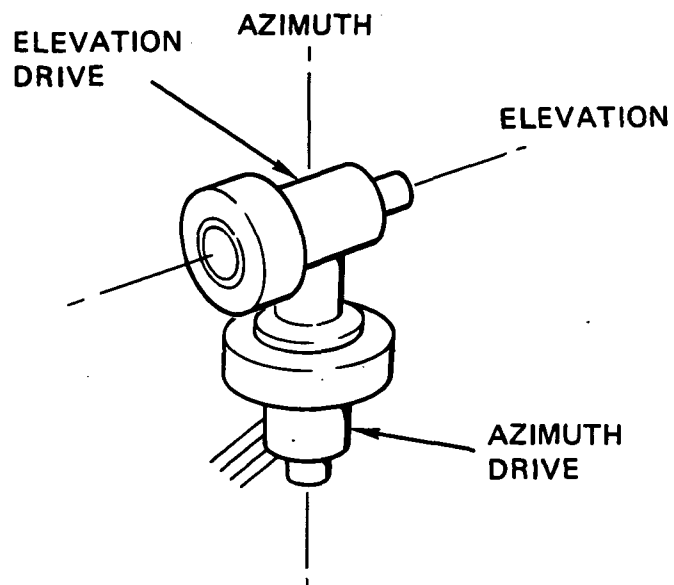
Due to the large RF compartment of the antenna (4.5 ft^3) and the large radiation surface (1.8 ft^2) required for TWT heat dissipation, it is not practical to incorporate a conventional gimbal design because the yoke becomes excessively large and it also blocks the radiation surfaces. In contrast, Figure 2-2 illustrates the adaptability of a U-shape RF compartment straddling the ADA. In the latter configuration, the RF compartment itself is the elevation gimbal structure and its radiator surfaces are not obscured by the ADA at any time. Some RF components are mounted below the elevation axis in the RF compartment, thus counter-balancing the antenna and reducing the torque moment reflected to the ADA.

Another significant advantage of configuration 3-1-b is its modular concept, in which the drive modules for both axes are identical and interchangeable. Furthermore, the standard drive module can be adapted readily for single- or multiple-axis applications.

Based on the considerations stated above, configuration 3-1-b is recommended for LandSat-D antenna drive application.



a. CONVENTIONAL ELEVATION/AZIMUTH GIMBAL DESIGN



b. MODULAR GIMBAL DRIVE DESIGN

Figure 3-1. Gimbal Design Configurations

4.0. RECOMMENDED ANTENNA DRIVE ASSEMBLY DESIGN

4.1 General Description

As mentioned previously, each ADA consists of two identical drive modules mounted in a T-configuration (see Figure 2-2). The antenna and RF compartment assembly is attached to the elevation drive module output shaft and the azimuth drive module housing is affixed to the end of the deployment boom. During launch or shuttle retrieval/landing, the antenna is latched to the upper portion of the boom so as to relieve shock loads to the ADA gimbal bearings.

Functionally, each drive module contains the following components:

Drive motor	- Permanent magnet stepper motor
Speed reducer	- Harmonic drive
Angle transducer	- Single speed resolver
Gimbal bearings	- Angular contact duplex ball bearings
Housing and shaft	- Titanium alloy
Cable wrap (Module)	- Flat ribbon cables and RF coaxial cables

Figure 4-1 shows the mechanical layout of the drive module. In construction, the motor shaft is coupled to the harmonic drive input through an Oldham coupling. The output shaft of the harmonic drive is connected directly to the gimbal output shaft, which is supported by a pair of ball bearings preloaded in a back-to-back fashion. A pancake type resolver is used for gimbal position information. Since the number of wires across each axis is extremely large - approximately 70 shielded wires plus 7 coaxial RF cables - the cable wrap design requires some attention in the area of torque, life, and reliability. (This is discussed in Section 4.4.7.) As shown in Figure 4-2, an adapter ring is used to join the elevation drive module to the azimuth module. The basic structure material is Titanium alloy (Ti-6Al-4V) - because of its high strength, light weight, and low thermal expansion.

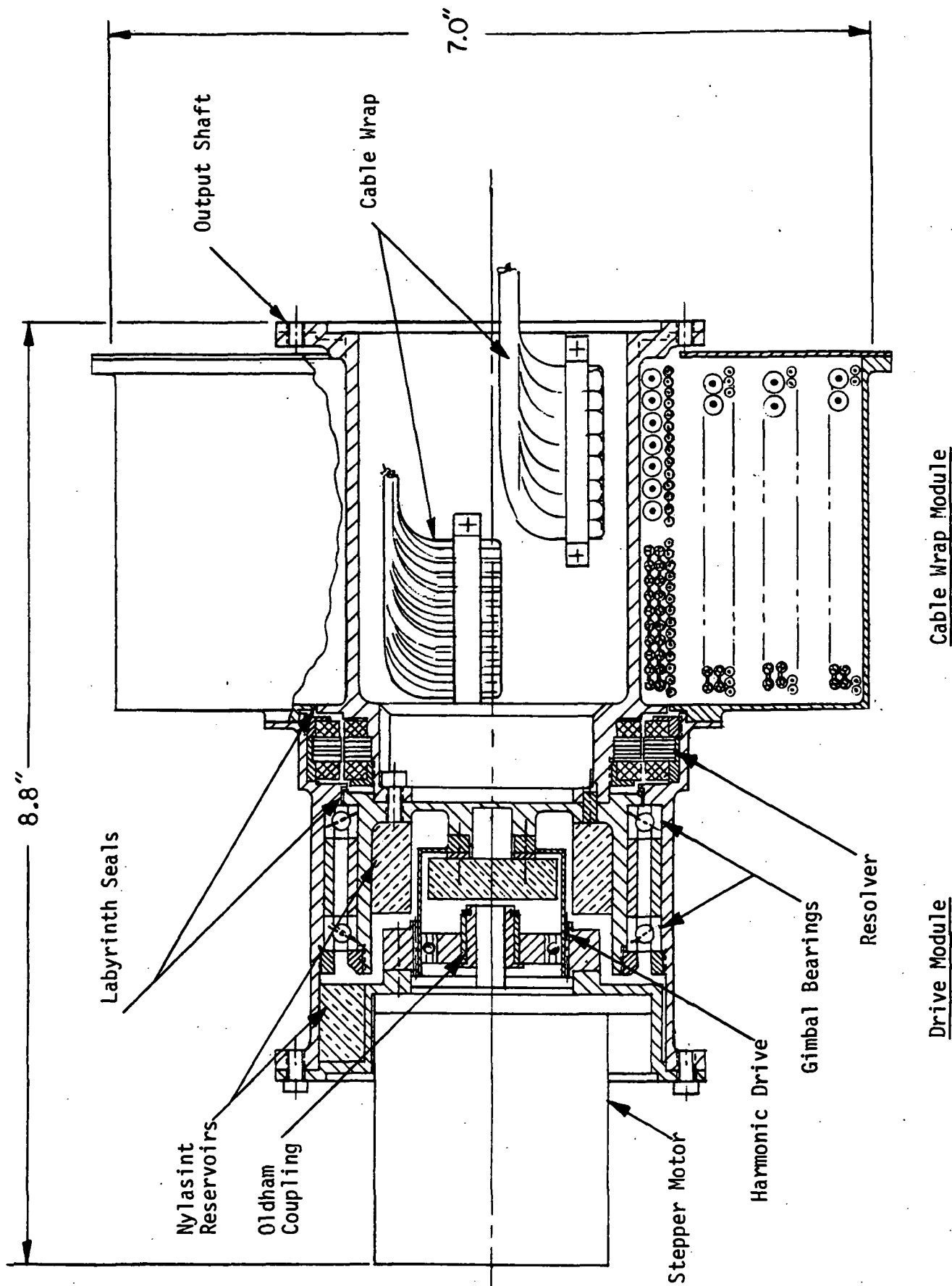


FIGURE 4-1. RECOMMENDED ANTENNA DRIVE MODULE

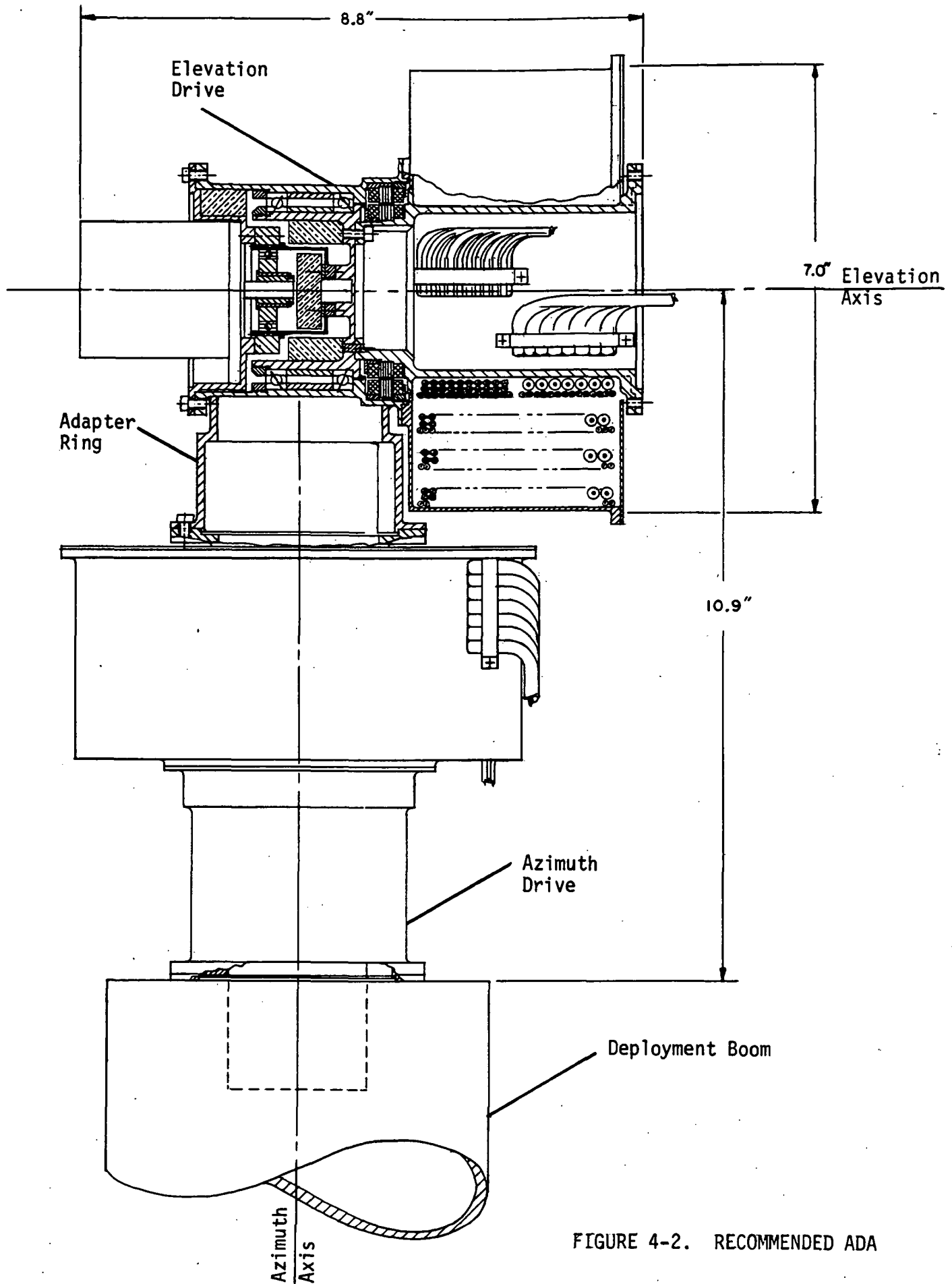


FIGURE 4-2. RECOMMENDED ADA

During operation, the stepper motor responds to sequential pulses from the drive electronics with incremental rotation of its shaft up to a maximum rate of about 250 steps per second. The motor shaft motion is transmitted to the drive module output shaft through a 100:1 ratio gear reducer (harmonic drive) with near-zero backlash. Because of the stepping integrity of the motor, open loop control is sufficient for most applications - no position or rate feedback is necessary. However, a position transducer is provided here for control loop error signal and for telemetry information. Another unique feature of the stepper motor is its detent torque, which provides considerable holding torque even with power removed.

The ADA design is substantially similar to the antenna and solar array drives developed and space-qualified by TRW for several space programs. Their reliability and performance capability have been established through extensive qualification testing and several years of flight history in space.

4.2 Performance Capability and Physical Characteristics

The recommended ADA can meet or surpass the performance requirements generated in the attitude control systems study performed by TRW, See Reference # 2. These requirements and capabilities are tabulated in Table 4-1. The physical characteristics and mass properties of the ADA are summarized in Tables 4-2 and 4-3, respectively.

4.3 Mounting Interface

The output shaft of the elevation drive modules mates with a mounting flange on one leg of the U-shape RF compartment. Electric connectors are provided for antenna and cable wrap interface. Likewise, the azimuth drive module housing is bolted directly to the boom through a mounting flange, but the electric connectors can be either at the ADA/boom interface or at the boom/MMS interface. Figure 4-3 shows the antenna in both the stowed and deployed positions.

TABLE 4-1. ADA PERFORMANCE REQUIREMENTS VS. CAPABILITIES

	Requirement*	Capability
Angular Freedom:		
Elevation	-28° to +208°	-28° to +208°
Azimuth	+200°	+200°
Output Step Size	<0.03 deg	0.018 deg
Slew Rate (maximum)	4 deg/sec	4.5 deg/sec
Tracking Rate	0.25 deg/sec	0.25 deg/sec
Acceleration (maximum)	0.5 deg/sec ²	>5 deg/sec ²
Pointing Accuracy	Better than 0.25 deg	0.2 deg
Readout Accuracy	Better than 0.20 deg	0.15 deg

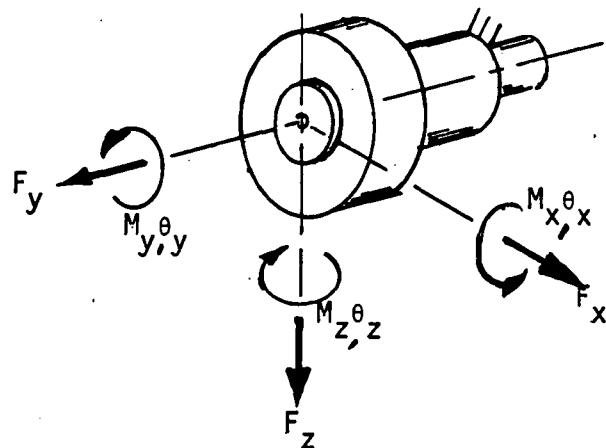
* As defined by the LandSat-D ACS Study being performed by TRW, Reference # 2.

TABLE 4-2. ADA PHYSICAL CHARACTERISTICS

GIMBAL CONFIGURATION:	ELEVATION OVER AZIMUTH (FIGURE 3-1b)
SIZE:	7" DIA X 8-3/4" EACH AXIS
WEIGHT:	
DRIVE MODULE -	5.2 LBS EACH AXIS
CABLE WRAP MODULE -	3.6 LBS EACH AXIS
BEARING CAPACITY:	
RADIAL -	1825 LBS
AXIAL -	5275 LBS
HEATER:	THERMOSTAT CONTROLLED HEATER FOR CABLE WRAP MODULE
THERMAL BLANKET:	FORMED MLI BLANKET
REDUNDANCY:	NONE
CAGING:	EXTERNAL CAGING REQUIRED FOR LAUNCH

STRUCTURAL COMPLIANCE, MAX:

δ_x/F_x (in/lb)	28×10^{-6}
δ_y/F_y (in/lb)	1.1×10^{-6}
δ_z/F_z (in/lb)	28×10^{-6}
θ_x/M_x (rad/in-lb)	2.5×10^{-6}
θ_y/M_y (rad/in-lb)	30×10^{-6}
θ_z/M_z (rad/in-lb)	2.5×10^{-6}



LIMIT LOADS:

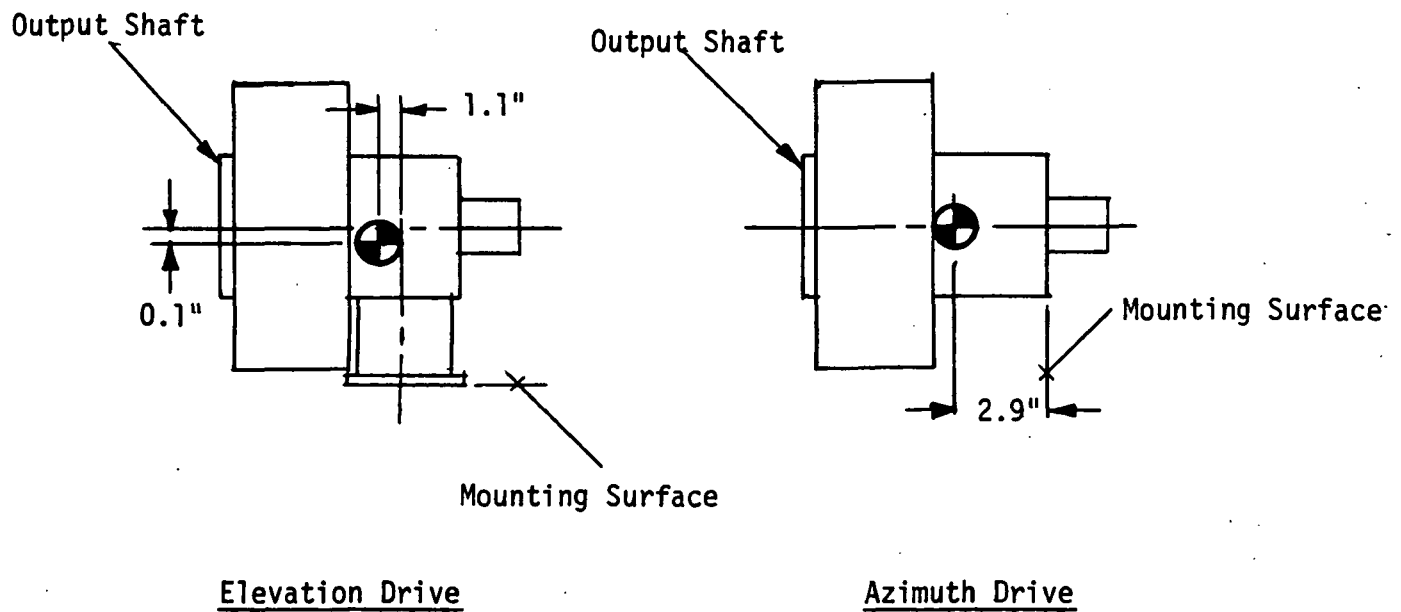
F_x (lb)	355	M_x (in-lb)	2,005
F_y (lb)	5,275	M_y (in-lb)	219*
F_z (lb)	355	M_z (in-lb)	2,005

*Torques exceeding this level will cause the motor to slip but without damage to ADA.

TABLE 4-3. ADA Mass Properties

<u>Weight (each axis)</u>	<u>Lbs.</u>
Stepper Motor	1.50
Harmonic Drive	.40
Gimbal Bearings	.40
Resolver	.65
Main Housing	1.27
Bearing Shaft	.82
Cable Wrap Housing	.45
Cable Wrap Shaft	.69
Cable Wrap and Connectors	2.45
Heater and Thermal Insulation	<u>.12</u>
	8.75

Center of Gravity



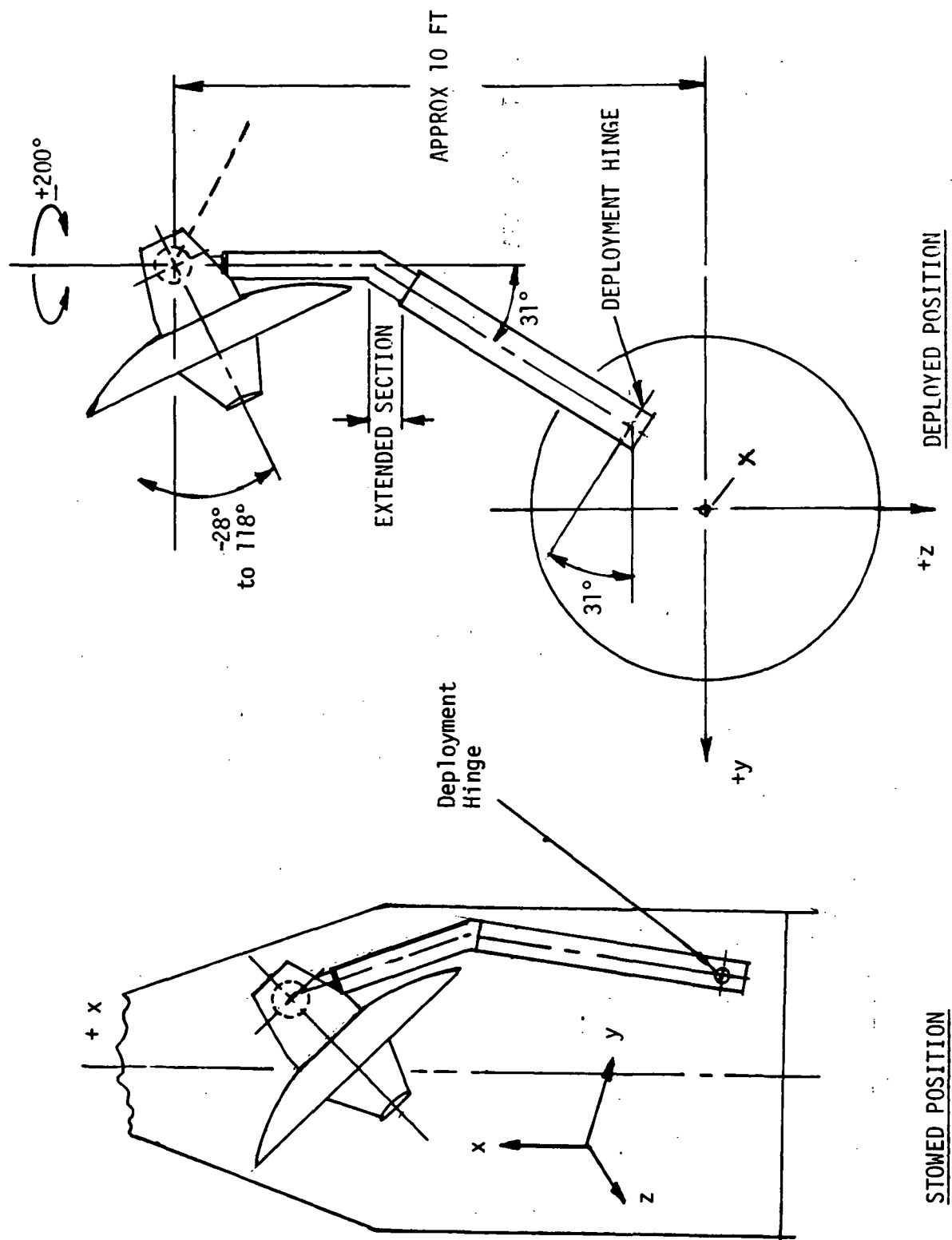


FIGURE 4-3. STOWED AND DEPLOYED POSITIONS OF ANTENNA

Due to the absence of a suitable structural support near the stowed antenna assembly, it becomes necessary to latch the antenna reflector to the deployment boom during launch and shuttle retrieval/landing. This arrangement can generate the following benefits:

- Relieve dynamic loading to the gimbal bearings
- Stiffens unsupported portion of the boom
- Eliminate caging mechanisms from the drive modules.

A simple latching mechanism is illustrated and described in Section 4.4.5. Figure 4-4 shows the complete 2-axis pointable antenna assembly in a stowed position within the allocated space.

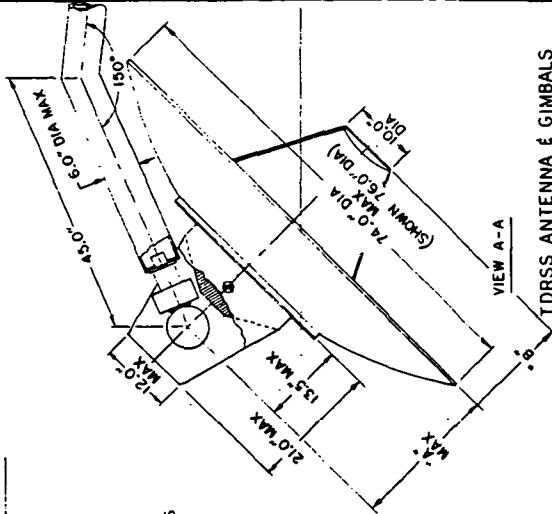
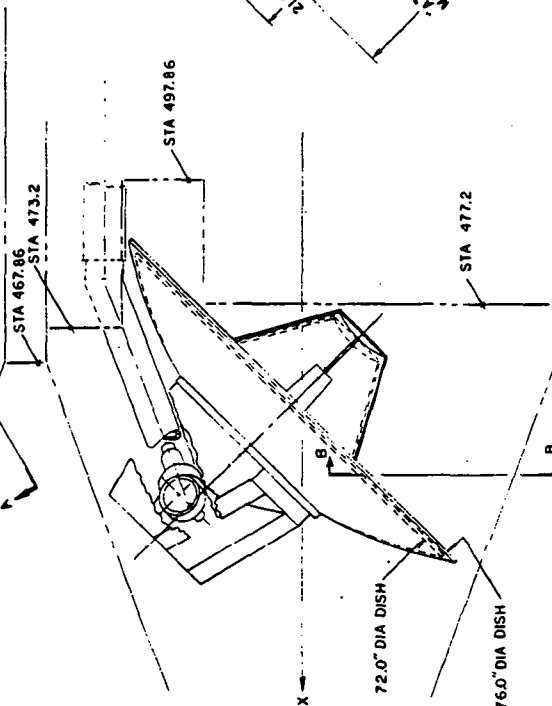
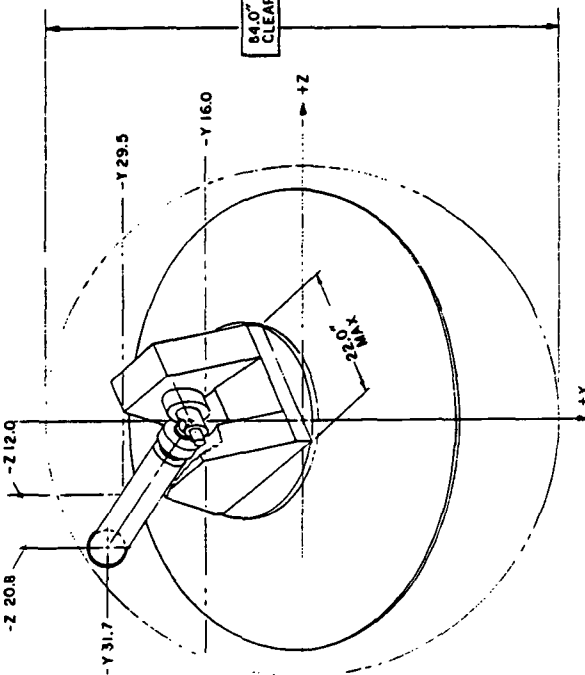
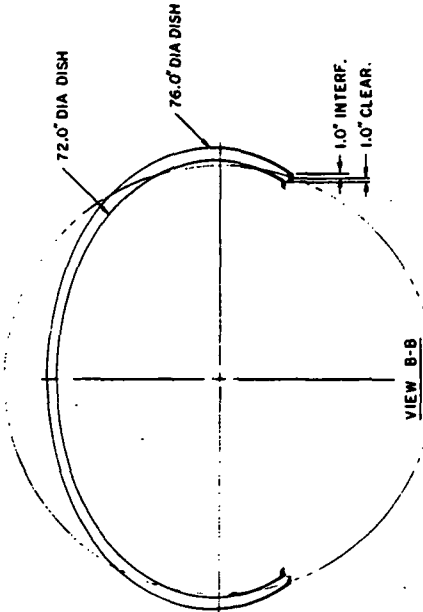
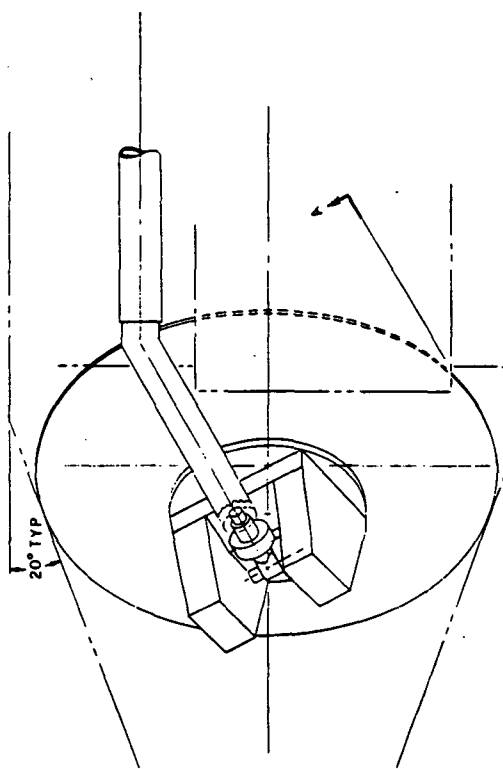
4.4 Drive Module Components Description and Tradeoffs

4.4.1 Motor

A stepper motor is selected over a dc motor for a myriad of considerations; some of them are outlined below:

- Stepper motor does not require rate or position feedback
- Does not have brush wear nor requires commutation devices
- Only requires simple switching circuits and bus voltage instead of complex servo loops
- Detent torque maintains position with power off
- For slow response applications, a stepper motor with speed reducer can provide better accuracy and higher output torque with less power input than a direct drive torquer.

The selected stepper motor is a Size 23, four-phase, permanent magnet, inductor-type stepping motor which directly converts sequential energization of the pulses to shaft output motion of 1.8 degree steps. The stator consists of eight wound poles, each pole having a number of teeth, at a pitch of 48 teeth for one complete cycle. The rotor consists of an axially charged permanent magnet with radially toothed end pieces, at a pitch of 50 teeth for one complete cycle. The motor operates by means of interaction between the rotor magnet dc flux and the stator magnetic flux generated by the applied current through a winding. Thus, by the pattern of winding energization and teeth distribution, the rotor advances a quarter of the rotor pitch with each switching sequence, i.e., 1/200 of a revolution, or 1.8 degree.



DISH	DIA	DIA	DIA
72.0	72.0	76.0	76.0
72.0	72.0	76.0	76.0
72.0	72.0	76.0	76.0

FIGURE 4-4. PACKAGING LAYOUT - ANTENNA AND ADA IN STOWED POSITION

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The energized stable equilibrium position also corresponds to the minimum reluctance position of a set of stator/rotor teeth. Therefore, by virtue of the permanent magnet flux, there is a "detent" or holding torque even when the winding is not energized. A restoring torque is generated whenever the rotor is backdriven from this minimum reluctance position.

The performance and physical characteristics of the stepper motor are summarized below:

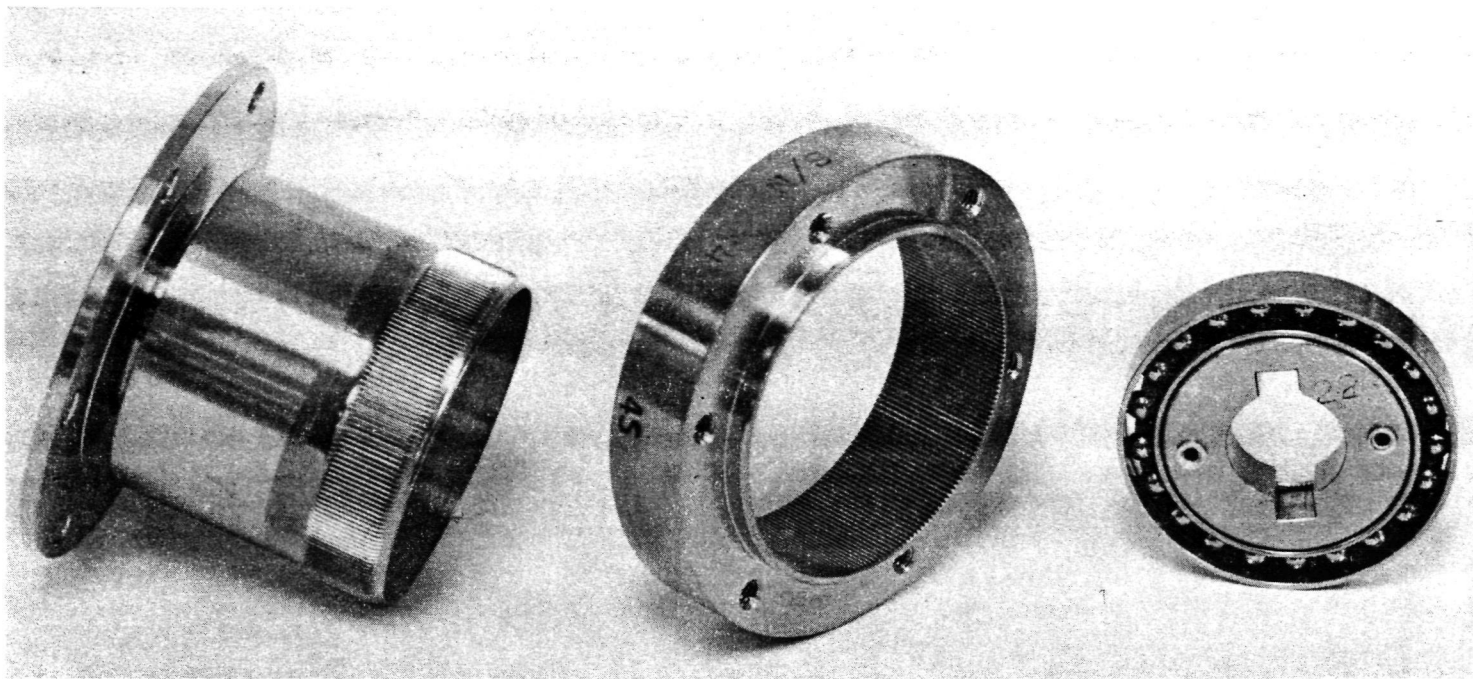
Motor size:	2.22" dia x 2.31" long
Step size:	1.8 degrees ± 15 percent (noncumulative)
Detent torque:	6.0 oz-in, minimum
Running torque:	13.0 oz-in, minimum at 200 steps/second
Stall torque:	30.0 oz-in, minimum
DC resistance per phase:	100 ± 10 ohms
Weight:	1.5 pounds, maximum
Input voltage:	28 ± 4 VDC
Maximum response:	350 steps/second

4.4.2 Speed Reducer

Within a given size, a harmonic drive has several advantages over a conventional geartrain, namely:

- Harmonic drive can generate high gear ratio (100 to 300:1) in a single pass
- High efficiency - $>90\%$
- Low backlash - as low as zero
- Multi-contact - high limiting torque
- High reliability - only two (2) moving elements.

The harmonic drive is a unique power transmission drive which provides high speed reduction in a compact assembly. It is composed of three basic elements: the circular spline, wave generator, and flexspline, as shown in Figure 4-5a. The elliptically shaped wave generator deforms the flexspline into an ellipse, so that teeth engagement with the circular spline occurs at diametrically

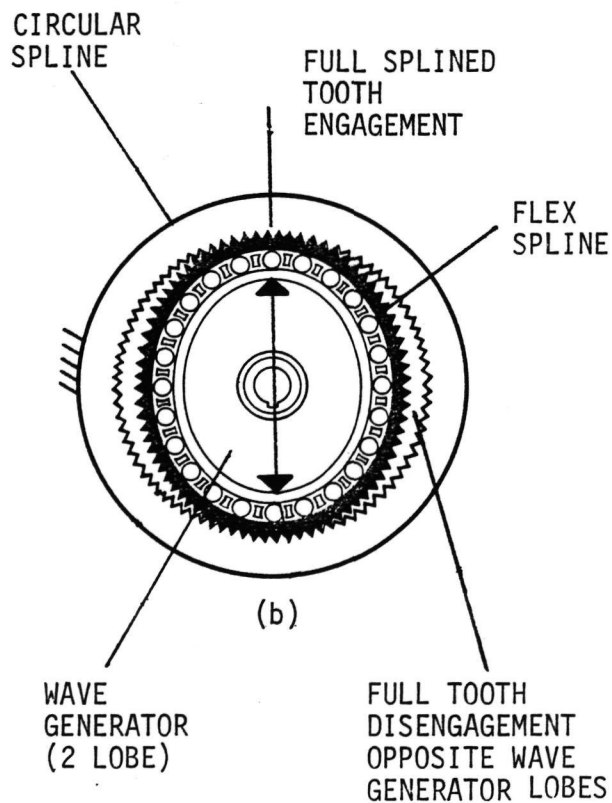


FLEXSPLINE

CIRCULAR SPLINE

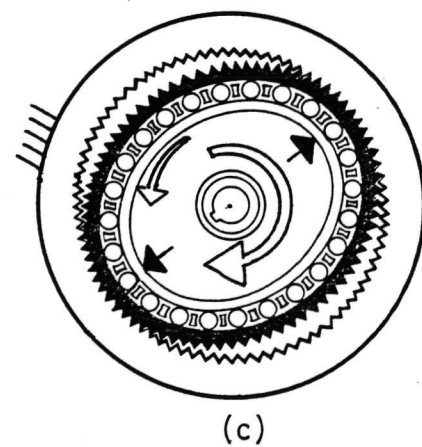
WAVE GENERATOR

(a) Harmonic Drive Components



(b)

FULL TOOTH
DISENGAGEMENT
OPPOSITE WAVE
GENERATOR LOBES



(c)

FLEXSPLINE
ROTATES
COUNTER-
CLOCKWISE

WAVE
GENERATOR
ROTATES
CLOCKWISE

FIGURE 4-5. HARMONIC DRIVE

opposite points. As the wave generator rotates, the shape imparted to the flexspline (but not the flexspline itself) rotates at the speed of the wave generator. Since the flexspline has two less teeth than the circular spline, relative movement occurs between the flexspline and circular spline as the wave generator advances the position of teeth engagement. Figure 4-5a shows that the circular spline is fixed and the flexspline (output) is rotating in the opposite direction from the wave-generator (input) but at a reduced rate. For each revolution of the wave-generator, the flexspline advances two teeth.

General characteristics of the harmonic drive are summarized below:

Pitch Diameter:	1.4 inch
Gear Ratio:	100:1
Positional Accuracy:	± 1.25 arc minutes
Torsional Stiffness:	30,000 in-lb/rad, minimum
Backlash:	Zero
Hysteresis:	± 0.75 arc minutes
Input Starting Torque:	5.0 in-oz, maximum
Maximum Output Torque:	200 in-lb
Weight:	0.4 lb

As seen in Figure 4-6b, about 10% of the gear teeth are in contact at all times; therefore, its load capability is high and the backlash is low. Because of the multitooth contact, the input starting torque is high (5 in-oz for zero backlash and 3 in-oz for 2 arc minute backlash). However, when used in conjunction with a stepper motor, this high starting torque has no detrimental effect to the drive system because the stepper motor is always pulsed with a fixed voltage (28 volt bus), thus producing a high output torque regardless of the load. Another potential problem associated with the high friction is wear of gear teeth. This problem is alleviated by the nature of design and by appropriate lubrication.

As shown in Figure 4-6c, only the wave generator ball bearing spins at a high speed (67 rpm maximum), whereas the flexspline (gear teeth) rotates at the output speed of $2/3$ rpm maximum during slew. This is quite a slow speed as compared with a cluster of gears in a conventional gear

train. The other factor influencing the harmonic drive life is the lubrication method. Sufficient development has been done in this area to assure proper lubrication for the gear. As incorporated in the previously developed drive mechanisms, the AISI 321 stainless steel flexspline teeth are gold plated per a specific procedure as a lubrication aid. Furthermore, a lubrication replenishment scheme is built into the drive module for the assurance of adequate supply of lubricant to the gear surface throughout its operating life in space.

Based on the manufacturer's data, the selected harmonic drive is rated to deliver a 75 in-lb load at an input speed of 1750 rpm for 5,000 hours, which is the B-10 (90% survival) life of the wave generator bearing. Also, the manufacturer has claimed through testing that there is no deterioration of performance due to tooth wear after 10,000 hours of operation at 1,750 rpm and 75 in-lb rated load. Therefore, the projected wave generator bearing life is: $1,750 \text{ rpm} \times 5,000 \text{ hours} \times 60 = 525 \times 10^6$ revolutions, and the gear teeth life is greater than $1,050 \times 10^6$ revolutions.

In the recommended ADA design, the average load torque is less than the detent torque of the motor, and it can be computed as follows:

$$\text{Average torque} < 6 \text{ in-oz} \times \frac{100}{16} \times .9 = 33.75 \text{ in-lb}$$

With an average of one $\pm 90^\circ$ rotations per orbit, the total input revolutions in a 5-year period can be computed as follows:

$$\begin{aligned} \text{Revolutions} &= \frac{4 \times 90^\circ / \text{orbit}}{360^\circ / \text{revol}} \times \frac{100}{1} \times \frac{24 \text{ hours/day}}{1.65 \text{ hours/orbit}} \times \\ &\quad 365 \text{ days/year} \times 5 \text{ years} \\ &= 2.65 \times 10^6 \text{ revolutions} \end{aligned}$$

Comparing the rated life of 525×10^6 revolutions at 75 in-lb load with the required life of 2.65×10^6 revolutions at 33.7 in-lb load, it is apparent that the selected harmonic drive in the recommended ADA has ample safety margin, provided a proper lubrication system is incorporated.

Incidentally, to eliminate the problem of axis alignment between the stepper motor and the harmonic drive, an Oldham coupler is installed between the motor shaft and the wave-generator, thus easing manufacturing tolerance, facilitating assembly, and assuring reliable operation.

4.4.3 Position Transducer

Both resolvers and potentiometers have been used in various drive modules developed for space applications. Due to the large angular excursion required of the LandSat gimbals, however, a pancake resolver is chosen.

Although a resistive-film potentiometer is smaller and lighter than most of the position transducers, it necessitates the use of gears to transfer output motion to the pot. With a one-to-one reduction, both gears are relatively large, which renders the packaging difficult and cumbersome. Additionally, the poor linearity of a potentiometer (0.1% of full scale) is only suitable for small angle applications where a large gear ratio can be advantageously utilized to reduce the linearity error by the same ratio. A multiturn wire-wound potentiometer can minimize the packaging and linearity problem, but its mechanical wear and low reliability makes it unattractive for space application.

An optical encoder can provide excellent accuracy in digital form, but it has the combined shortcomings of large size, heavy weight, and requiring gears for packaging reasons. Table 4-4 lists some comparative features of three (3) different types of position transducers. On balance, a single speed pancake resolver is considered the best choice for the LandSat ADA.

The sine-cosine outputs of the resolver are transformed into 12-bit data through a resolver-to-digital converter for servo control as well as telemetry information.

The selected characteristics are summarized below:

Size:	3.374" OD; 2.249" ID; .420" thick
Weight:	.65 lbs
Speed:	Single
Excitation:	28 volt; 400 or 1,200 Hz

TABLE 4-4. COMPARATIVE FEATURES OF POSITION TRANSDUCERS

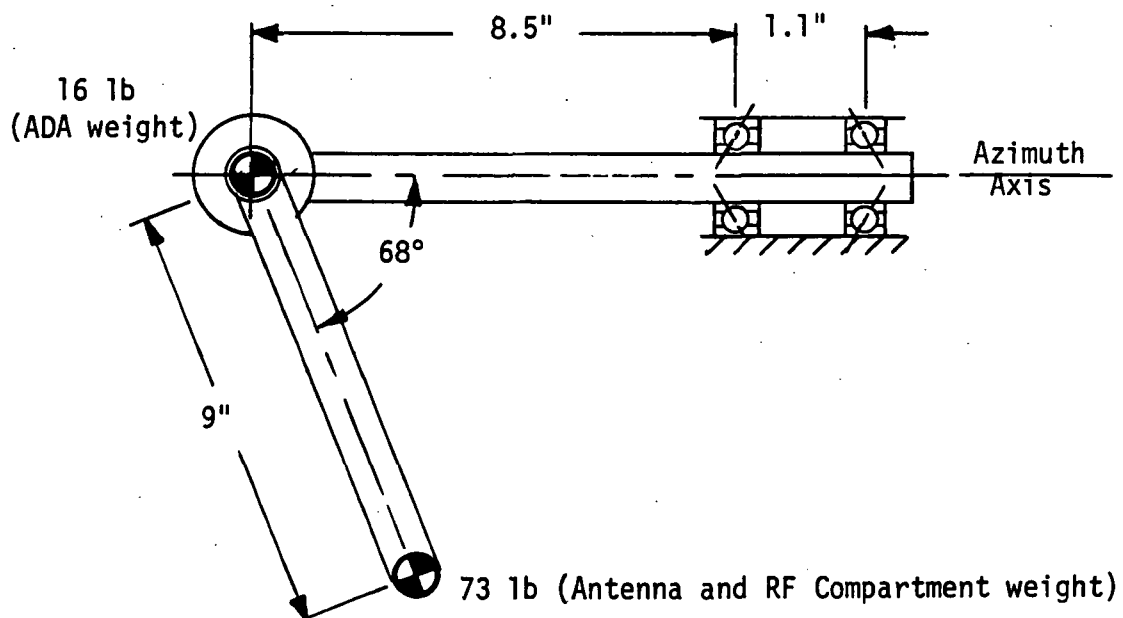
	Potentiometer Resistive Film	Optical Encoder 12-bit	Pancake Resolver Single Speed
Accuracy, arc minutes	20	5	5
Resolution, arc minutes	Infinite	5	Infinite
Excitation	Regulated 5VDC	Regulated 5 VDC	28V, 400 Hz
Outputs	Analog	Digital	Analog
Ball Bearings	Required	Required	Not required
Reliability	Mechanical Wipers	Light Source	No wear, no lamp
Size	1-1/8" dia x 3/4"	2-17/32" dia x 3/5/8"	3-3/8"OD, 2-1/4"ID, .42"t
Weight, lbs	0.04	1.1	.65
Cost	Low	High	Medium
Installation	Require gears	Require gears	Direct mounting
Packaging for ADA (+200° rotation)	Difficult	Difficult	Easy
Data Processing	A/D Converter	--	A/D Converter

Transformation Ratio:	1.00
Accuracy:	5 arc minutes
Rotation:	360° (unlimited)

4.4.4 Gimbal Bearings

The output shaft of each drive module is supported by a pair of angular contact ball bearings preloaded with a set of preground spacers, which assures a minimum preload variation over the full temperature range. The back-to-back configuration is for the obvious reason of improved moment rigidity.

In the stowed condition as shown in the schematic diagram below, the radial loads are computed to be 555 pounds on the front bearing and 465 pounds on the rear bearing in 1-g environment. Based on the environmental inputs specified for LandSat III, shown in Figure 4-7, a maximum of 24-g could be realized by the ADA bearings.



The maximum static bearing load capacity can be computed from the following expressions:

Acceleration (for analysis)

Thrust 24g

Lateral 4g

Sinusoidal Vibration

Frequency Range (Hz)	Amplitude - "g" 0-to-peak	
	Thrust	Transverse
5-30	7.5*	
30-100	11.0	
100-2000	5.0	
5-200		7.5
200-2000		5.0

*Exposure limited to 0.5" double amplitude.

Sweep rate: 4 octaves/minute

Random Vibration

Frequency Range (Hz)	Power Spectral Density (g^2/Hz)	g-RMS	Duration
20-300	.0023 to .090	12.8	1 min/axis
300-2000	at 4 db/oct .090		

Launch Shock

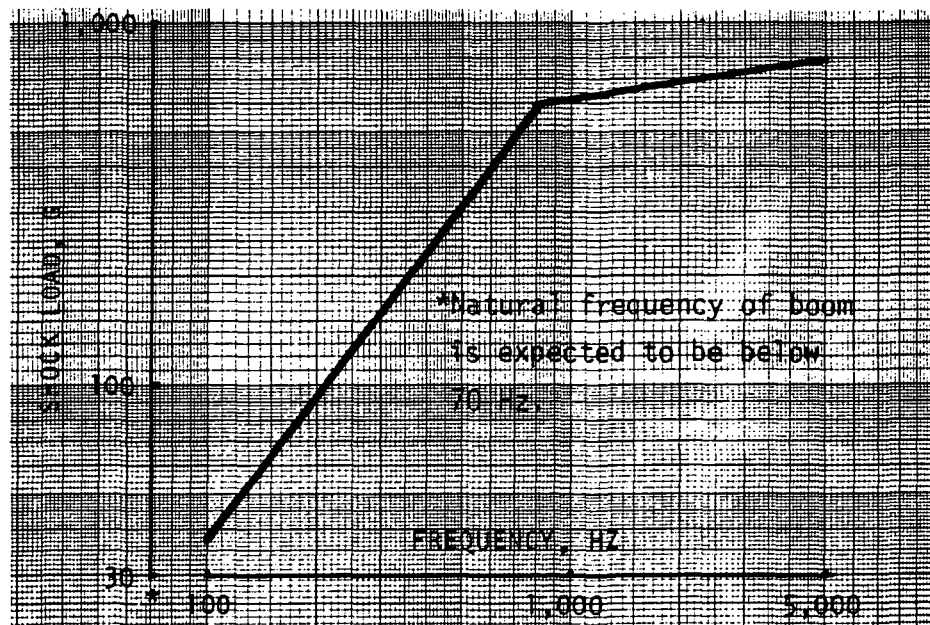


FIGURE 4-6. ENVIRONMENTAL SPECIFICATION - LANDSAT III

$$C_s = 400 i Z D^2 \cos \alpha \left[\frac{2f(1+\gamma)}{2f-1} \right]^{1/2} \quad \text{Radial} \quad (\text{Reference \# 4})$$

$$C_{sa} = 2,000 i Z D^2 \sin \alpha \left[\frac{2f(1+\gamma)}{2f-1} \right]^{1/2} \quad \text{Axial} \quad (\text{Reference \# 4})$$

Where:

C_s = Static radial capacity, pounds

C_{sa} = Static thrust capacity, pounds

i = Number of rows of balls = 1

α = Nominal contact angle = 25°

Z = Number of balls per row = 27

D = Ball diameter = $3/16$ inch

f = Geometry factor = .52

γ = $D \cos \alpha / d_m$

d_m = bearing pitch diameter = 2.8125 inch

γ = $(.1875) \cos 25^\circ / 2.8125 = .06$

$$\therefore C_s = (400)(27)(.1875)^2 \cos 25^\circ \left[\frac{2(.52)(1-.06)}{2(.52)-1} \right]^{1/2}$$

= 1,701 pounds (radial capacity)

$$\text{and } C_{sa} = 2,000(27)(.1875)^2 \sin 25^\circ \left[\frac{2(.52)(1-.06)}{2(.52)-1} \right]^{1/2}$$

= 3,966 pounds (thrust capacity)

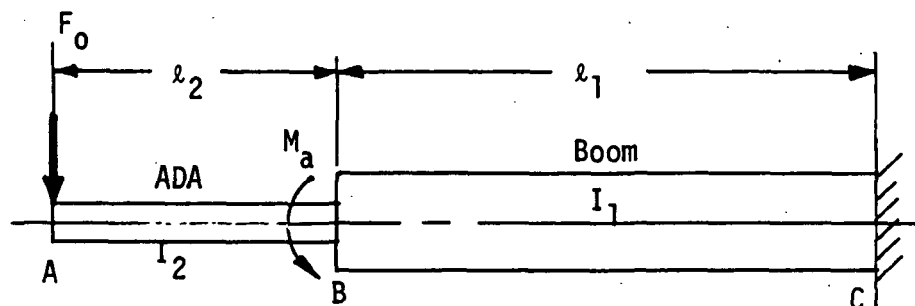
It is apparent, therefore, that the ADA bearings can only withstand a 3-g load; which is far below the 24-g's expected from Figure 4-7.

Although a larger set of bearings can be selected to accommodate the g loads, the resultant size and weight increases do not justify such an approach, as evidenced in Table 4.5. One direct effect of such large bearings is the consequent load increase to the deployment boom, and the other effect is the increased bearing friction. Therefore, the recommended solution is to incorporate a latching mechanism, which cages the antenna assembly to the deployment boom during launch, automatically releases it just prior to deployment, and then recages it under command for retrieval.

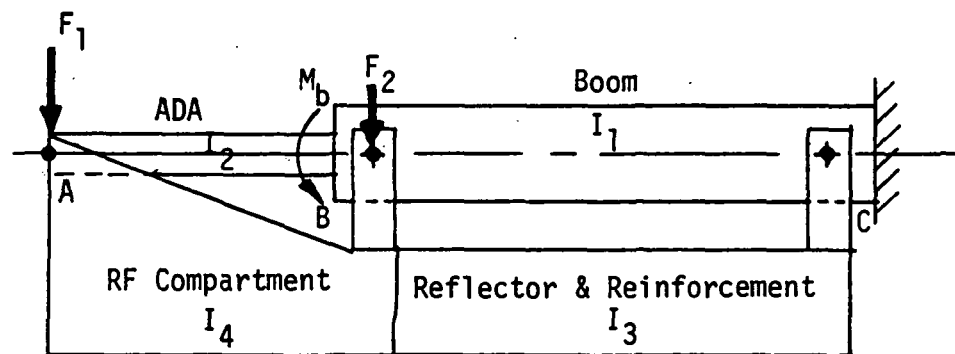
4.4.5 Caging Mechanism

In order to relieve radial loads to the antenna drive assembly bearings, it is necessary to support the antenna assembly at two points, as depicted in Figure 4-7. With the two latching arms properly mounted to the antenna assembly, they are secured to the deployment boom through a common or two separate caging mechanisms.

Schematically, the unlatched and latched conditions are illustrated in the diagram below:



a. Unlatched Condition



b. Latched Condition

TABLE 4.5 GIMBAL BEARING COMPARISON

CHARACTERISTICS	KAYDON BEARING P/N		
	KB025*	KB055	KG042
Static Load Capacity, lbs	(Manufacturer's Rating)		
Radial	1,825	3,200	8,550
Axial	5,275	8,050	21,300
Size, inches			
OD	3.125	6.125	6.250
ID	2.500	5.500	4.250
Width	0.3125	0.3125	1.000
Ball Diameter	0.1875	0.1875	0.500
Weight, lbs			
Bearing (pair)	0.4	0.8	7.6
Spacers (set)	0.2	0.8	0.7
Housing	0.9	1.83	1.92
Shaft	<u>0.4</u>	<u>1.03</u>	<u>0.74</u>
Total Weight, lbs	1.9	4.46	10.96
Bearing Friction, in-oz	1.0	12.0	5.0
g-load Capacity (in ADA)	2.8	5.8	15.4
Required Capacity, g (without external support)	<u>24</u>		

* Selected for the recommended ADA design.

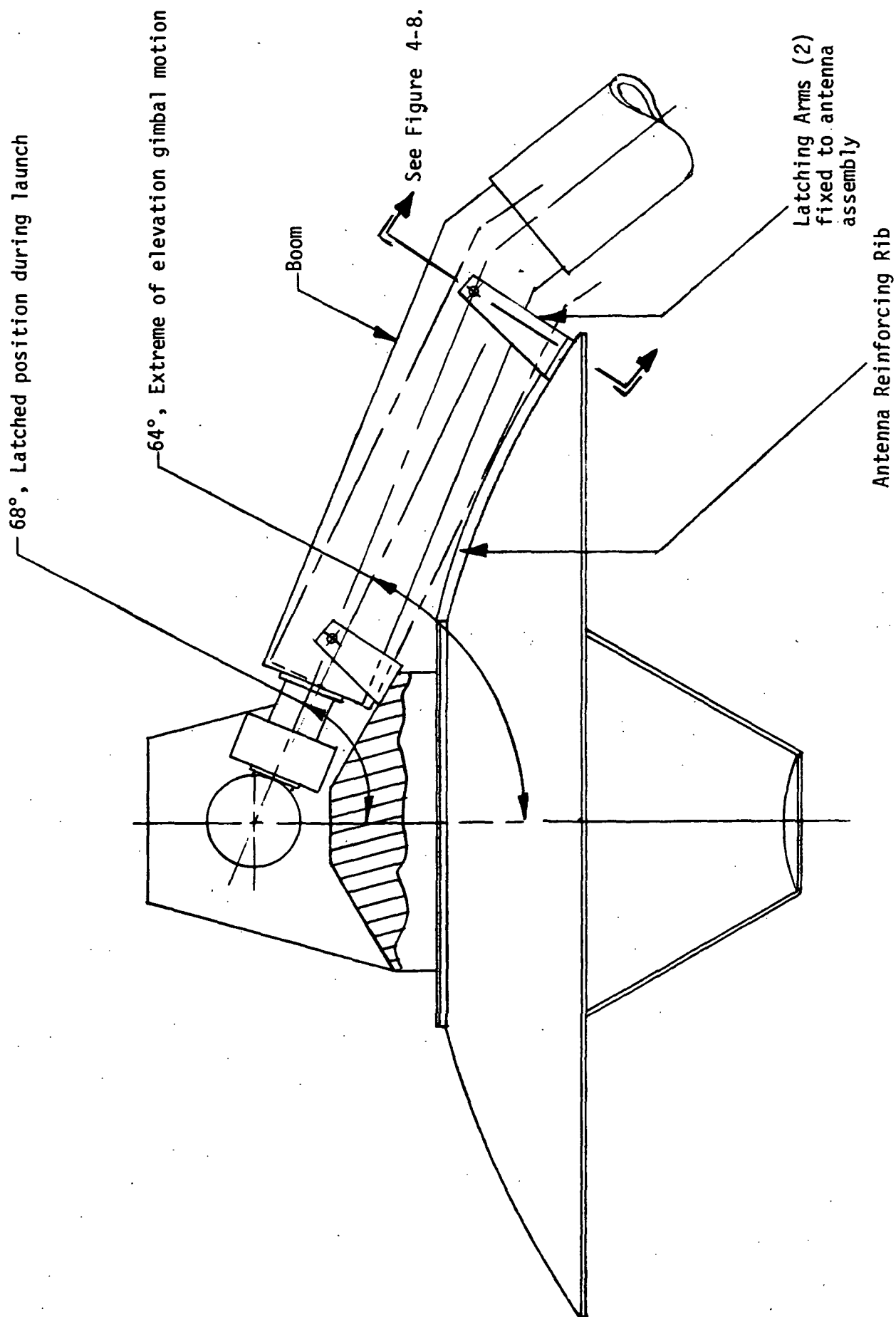
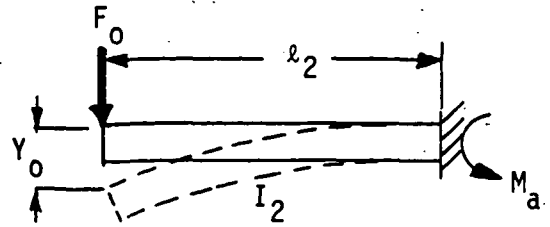


FIGURE 4-7. METHOD OF ANTENNA LATCHING

In case (a):

$$M_a = F_o \ell_2 = \frac{3E_2 I_2}{(\ell_2)^2} (y_o)$$



In case (b), the load is mostly transmitted directly to the boom ($F_2 \gg F_1$) because of the relatively high rigidity of the RF compartment and reinforced reflector. Preliminary analysis has yielded the following comparative estimates of moment of inertia:

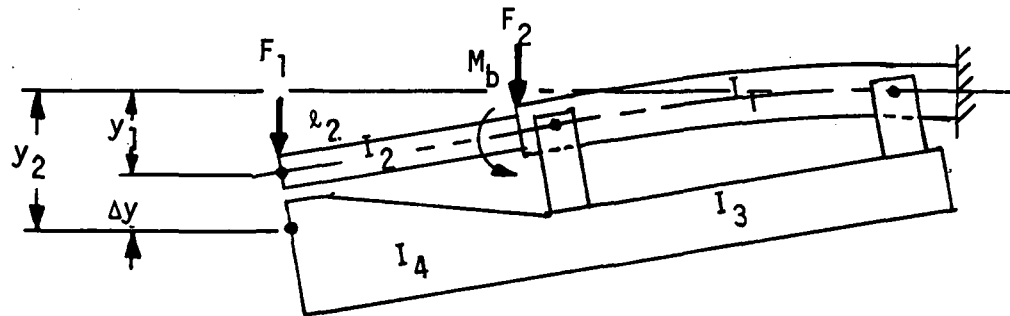
$$\text{Boom} - I_1 = 83.2 \text{ in}^4$$

$$\text{ADA} - I_2 = 1.73 \text{ in}^4$$

$$\text{Reinforced reflector} - I_3 = 110.9 \text{ in}^4$$

$$\text{RF compartment} - I_4 = 500 \text{ in}^4$$

From the diagram below, it can be seen that the bending moment M_b is generated by deflection Δy .



With the RF compartment disconnected from the ADA:

$$F_1 = 0, M_b = 0$$

In order to join the RF compartment to the ADA, F_1 must be applied to point A for a deflection Δy .

Therefore,

$$\Delta y = \frac{F_1 \ell_2^3}{3E_2 I_2}, \quad M_b = F_1 \ell_2$$

and

$$M_b = \frac{3E_2 I_2}{\ell_2^2} (\Delta y)$$

Since Δy is calculated to be $y_0/16$, the radial loads reflected to the ADA bearings are expected to be 16 times less in case (b) than that in case (a). This ratio can be further improved in the final design of the deployment boom and the antenna reflector reinforcing rib.

As to the latching mechanism itself, a conceptual design is suggested in Figure 4-8. Two caging pins, one with left-hand threads and the other with right-hand threads, can be extended or retracted by the rotation of a threaded worm wheel assembly, which is driven by a small (size 11) DC motor. Dry lubricant can be used for all the moving parts.

The antenna assembly is caged to the deployment boom when both latching arm assemblies are held in place by the extended caging pins. After launch but prior to deployment, the pins are retracted so that the arms are freed from the boom. Since the arms are symmetrical about the boom and also the azimuth axis, they do not interfere with the azimuth rotation even in the extremes of elevation attitude.

For retrieval operation, the antenna can be commanded to the latching position (a preset azimuth and elevation angle); then the caging pins can be subsequently extended to secure the latching arms. Because all the pins have conical heads, slight misalignment between the pins and holes (± 15 steps or $\pm 25^\circ$) will not hinder the relatching operation. Simple LED-photodiode detectors can be incorporated to aid the caging-uncaging procedures.

4.4.6 Lubrication

As typical with all instrument designs for space application, lubrication design is a critical item of the system because of its potential

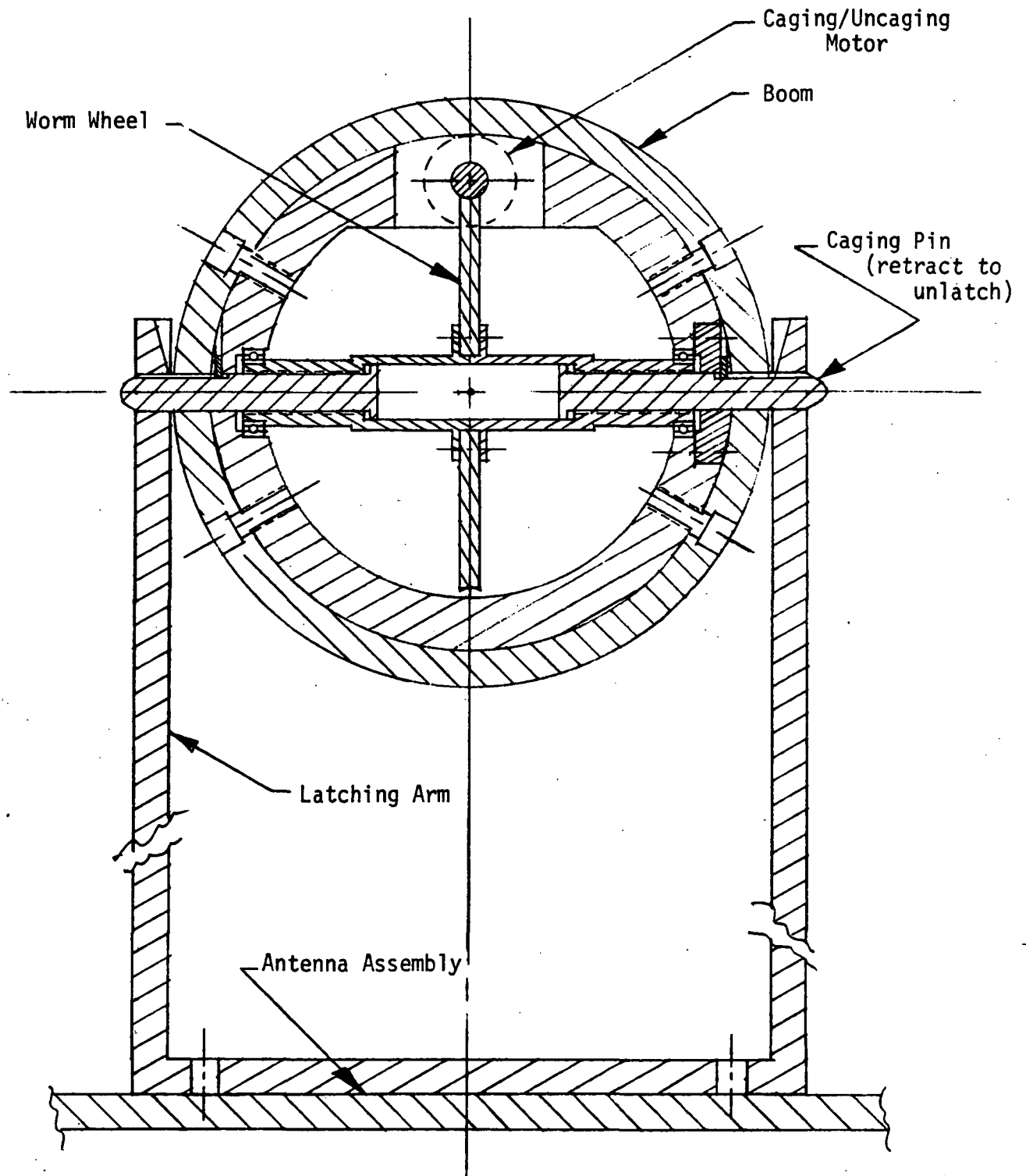


FIGURE 4-8. CAGING MECHANISM
(APPROX. 1/2 SCALE)

detrimental effects to the entire system or even to the mission. Although some dry lubricants such as Vackote, MoS_2 film, electrofilm, etc., all have demonstrated certain degrees of success, especially for special requirements such as extreme temperatures, inorganic materials, or inside optical instruments, these dry lubricants are generally avoided by most engineers when reliability and long operating life are the primary objectives.

Dry lubricant can be applied either by impinging the bearing surface or by coating the surface with chemical binders. Both processes require the highest quality control during manufacturing, and their low yield rates further push the bearing cost to a very high level. Aside from economics, the unpredictable nature of bare spots or lubricant film peeling off does not assure a good reliability, especially for continuous operation over a long period of time. High friction, poor heat distribution, particulate contamination, and long run-in requirements are the other undesirable features of dry lubrication.

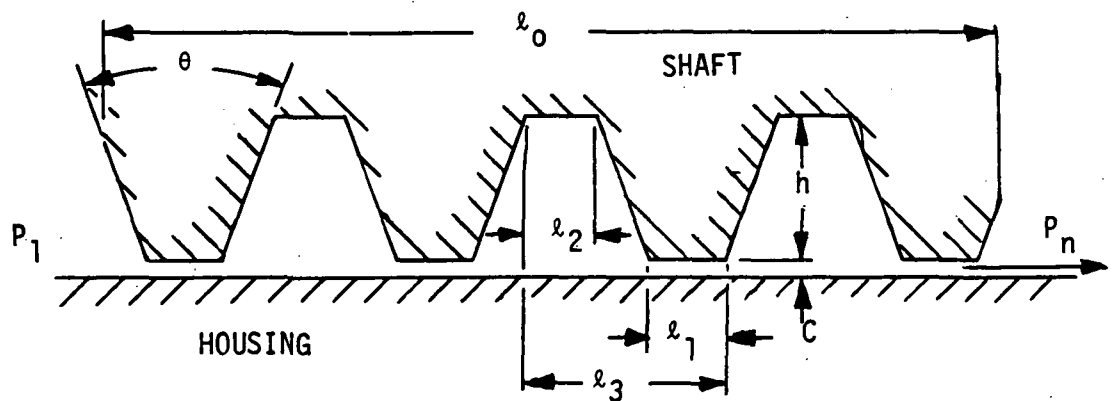
Typically, in a wet lubrication scheme, the ball bearing's phenolic retainer is vacuum impregnated with the specified lubricating oil, which is continuously distributed to the bearing balls and raceways through the bearing's rotational motion. In a vacuum environment, however, the lubricant will evaporate and escape from the instrument cavity even if a contact or non-contact seal is provided. To assure a sufficient replenishment of the lubricant during the duration of Landsat's operational life, lubricant reservoirs are incorporated into the instrument design.

As seen in the ADA layout, Figure 4-1, a Nylasint reservoir is placed adjacent to each bearing or gear assembly. In theory, as the ambient pressure drops below the lubricant vapor pressure, the oil molecules will escape from the reservoir surface and scatter into the instrument cavity. Since the bearings and gears are in the immediate vicinity of the reservoirs and directly exposed to the escaping oil molecules, the oil molecules will most likely deposit on the bearings and gears. Furthermore, all surfaces inside the instrument cavity are precoated with lubricant during assembly so that this large surface area will aid in the resupply mechanism.

Of course, this lubricant transport mechanism is so complex and its successful operation depends on several variables such as component temperature, operating speed, type of lubricant, physical configuration, and other design details. Nevertheless, two facts are providing the positive aspect for this lubrication design: operating conditions and performance history.

Because the operational speed of the ADA is extremely low, .25°/sec, negligible heat is generated in the bearings. Furthermore, the thermal analysis has verified that the stepper motor and the cable wrap housing are warmer than the main housing, where the bearings are located. (See Figures 4-13, -14, -15, and Tables 4-9, -10.) Therefore, the lubricant will more probably condense on the cooler bearings rather than on the warmer ends of the assembly. The other positive aspect is the performance history - TRW has successfully employed this lubrication scheme in all its gimbal drives already space-flown or space-qualified.

In order to minimize lubricant evaporation in a vacuum environment, a labyrinth seal (non-contact) is designed into the instrument to attenuate the flow of oil molecules. The labyrinth seal geometry and its attenuation factor are illustrated below.



$$\text{Attenuation Factor: } f = K \left[\frac{1 - \frac{P_n}{P_1}}{N - \frac{P_n}{P_1}} \right]^{1/2} \left[1 - \frac{8.52}{(\ell_3 - \ell_1)/c + 7.23} \right]^{-1/2} \quad \text{--- Reference \# 5}$$

- where:
- $\ell_1 \leq 0.005"$
 - $\ell_2 = 0.015"$
 - $\ell_3 = 0.046"$
 - $c = 0.005"$
 - $h = 0.035"$
 - $\theta = 40^\circ$
 - $K = \text{clearance factor} = 0.65$
 - $N = \text{number of seal points} = \ell_0/\ell_3 = 4$
 - $P_n = \text{pressure of the last seal point} = 10^{-9} \text{ in Hg}$
 - $P_1 = \text{vapor pressure inside ADA} = 10^{-6} \text{ in Hg}$

The attenuation factor is computed to be .291 for the recommended ADA seal design. Based on this attenuation factor, the oil loss over a 3-year period can be estimated by the following equation:

$$W_\ell = fQAt$$

- where:
- $W_\ell = \text{quantity of oil loss, grams}$
 - $f = \text{attenuation factor} = .291$
 - $Q = \text{evaporation rate of NPT-4} = 0.6 \times 10^{-4} \text{ gr/cm}^2/\text{Hr (at } 70^\circ\text{F)}$
 - $A = \text{duct area} = 0.284 \text{ cm}^2$
 - $t = \text{operating time} = 3 \text{ years} = 26,280 \text{ hours}$

$\therefore W_\ell = 0.13 \text{ grams/3 years}$, and the corresponding volume of this oil loss is:

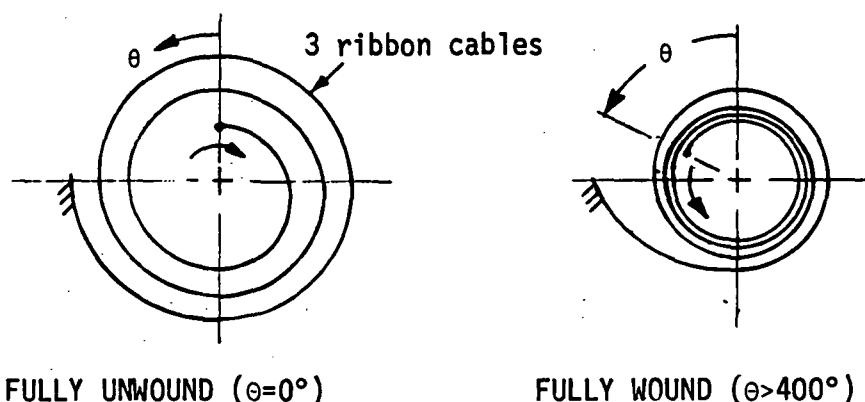
$$V_\ell = W_\ell / \rho = 0.13 \text{ grams} / 0.95 \text{ grams/cm}^3 = 0.14 \text{ cm}^3$$

With a 6 cm³ Nylasint reservoir of 40% porosity installed inside the ADA, it is apparent that the oil supply has a safety margin of 17 over the estimated depletion rate.

The motor bearings, harmonic drive bearings, and gear teeth all use the same type of lubricant and share the same replenishment reservoirs for the gimbal bearings.

4.4.7 Cable Wrap

All the electrical wires across the gimbal axes and their respective functions are listed in Table 4.6. Because of the wide rotational range and large number of cycles, a single service loop cannot adequately meet the torque and life requirements. Furthermore, for environmental and handling considerations, it is better to enclose the cable assembly inside a protective housing than to leave it in the open. After some design tradeoffs, the selected configuration is a set of three ribbon cables - the first one with 31 single shielded wires, the second one with 20 shielded pairs, and the third one with 7 coaxial cables tied in a flat strip - coiled up in a concentric spiral wrap as shown below:



Ribbon cables are more flexible and have a longer flex life than round cables or bundles because all the wires are in the same plane. Consequently, they offer minimum resistance to the curvature of a bend and experience minimum stress.

TABLE 4-6. CABLE WRAP WIRE LIST

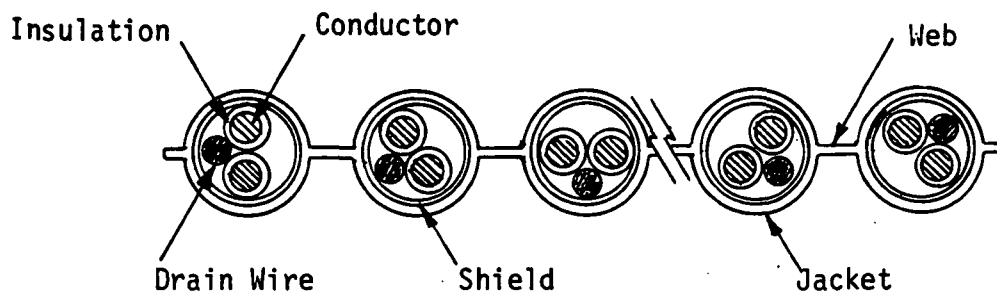
Function	Type and Size of Wire	No. of Wires
<u>RF Compartment:</u>		
Telemetry	Single shielded #26 AWG	20
TLM return	Single shielded #26 AWG	1
Relay switching	Single shielded #26 AWG	6
Digital interface	Single shielded #26 AWG	2
Relay switch return	Single sheilded #26 AWG	1
Coax - 3 GHz	Coaxial GMCA*	1
- 2 GHz	Coaxial GMCA*	1
- 250 MHz	Coaxial GMCA*	1
- Digital signals	Coaxial GMCA*	4
Switching oscillator	Shielded pair #26 AWG	1 pr
Power - +28V (3.0A)	Shielded pair #26 AWG	4 pr
- +15V (.05A)	Shielded pair #26 AWG	1 pr
- +5V (.17A)	Shielded pair #26 AWG	2 pr
- -5V (.45A)	Shielded pair #26 AWG	5 pr
<u>ADA</u>		
Motor	Shielded pair #26 AWG	2 pr
Motor	Single shielded #26 AWG	1 pr
Resolver	Shielded pair #26 AWG	3 pr
Heater	Shielded pair #26 AWG	1 pr
Thermostat	Shielded pair #26 AWG	1 pr
TOTAL	Single shielded #26 AWG	31
	Shielded pair #26 AWG	20 pr
	Coaxial GMCA*	7

* GMCA is equivalent to RG-400.

Note: Size of conductors can be increased for the cables along the deployment boom.

Minimum inside diameter of the wrap is dictated by the minimum bend radius of the coaxial cable, and the minimum outside diameter is determined by the fully unwound dimension of the wrap. In the recommended cable wrap design, the shaft diameter is 2.75 inches, the housing diameter is 7.0 inches, and the cable length of each wrap is 4.0 feet.

A ribbon cable generally consists of shielded singles or pairs laid flat and parallel to each other and then laminated between homogeneous Teflon jackets as illustrated below:



For greater flexibility, the conductors are made of 19 strands instead of the usual 7 strands. After being insulated with Teflon PTFE resin, in accordance with MIL-W-16878D, the wires are twisted into pairs together with a bare drain wire, shielded with helically wrapped aluminized Mylar or Kapton tape, and then formed into a ribbon with homogeneous Teflon jackets and webs. This particular type of shield construction affords maximum shielding effectiveness, excellent flexibility, and lightest weight as compared to a braided shield. The single conductors are shielded with served copper wire, again for better flexibility and lighter weight than braided shielding.

The seven coaxial lines are laid flat and spot-tied into a ribbon configuration. To improve flexibility and electrical performance, a new coaxial cable using expanded polytetrafluoroethylene (PTFE) as its dielectric is selected. Due to the expanded (porous) characteristics of PTFE, this so-called "Gore-Tex" cable, manufactured by W. L. Gore and Associates, Inc., not only exhibits good flexibility and lower thermal expansion than RG-400, but also offers lower insertion loss than RG-142B. A comparison between three different coaxial cables are tabulated in Table 4-7.

TABLE 4-7. COAXIAL CABLE COMPARISON

	RG-142B	Astroflex 32000	GMCA-190
MANUFACTURER	TENSOLITE	ASTROLAB	W. L. GORE
CABLE SIZE:			
CENTER CONDUCTOR	.040" DIA	19/.0077"	19/.011" DIA
OUTSIDE DIAMETER	0.190" DIA	0.170" DIA	0.190" DIA
WEIGHT, LB/FT	0.043	0.035	0.029
INSERTION LOSS, db/10 FT			
1 GHz	1.3	1.3	0.8
2 GHz	---	2.13	1.3
3 GHz	2.6	2.69	1.7
SPRING RATE*, IN-OZ/DEG	0.064	0.025	0.028
FRICTION*, IN-OZ (MAX) (HYSTERESIS, FRICTION)	17	10	17

*Single coaxial cable coiled into the configuration of ADA cable wrap design.

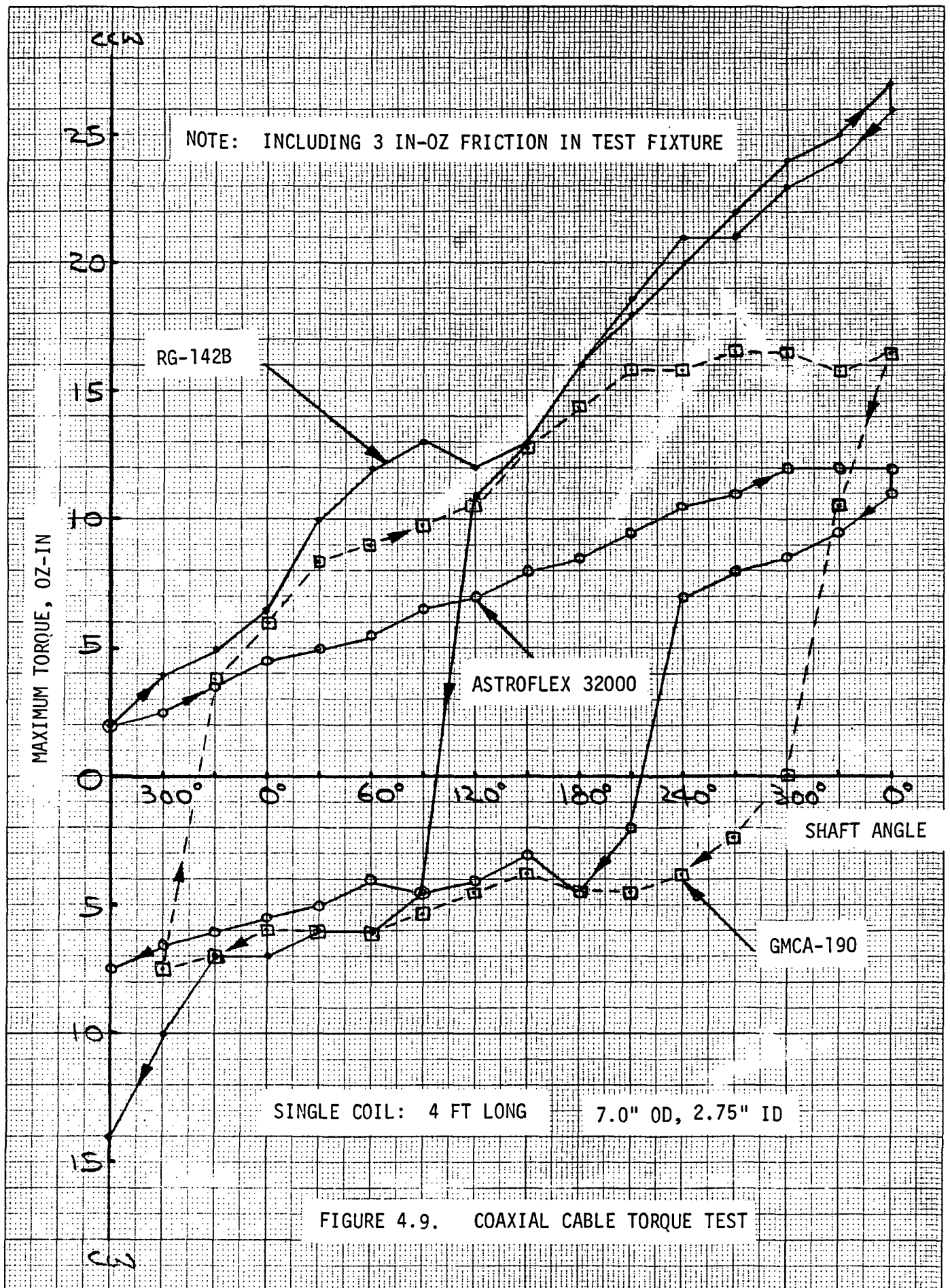
Based on the manufacturer's publications, the expanded Teflon dielectric material offers the following advantages:

- Low dielectric constant (below 1.3) - electrically homogeneous and stable in density, permitting the use of the coax over the entire frequency band.
- Small and light - for a given impedance and attenuation, low dielectric constant permits smaller core and resultant lighter cable.
- Flexibility - porous core and smaller cable contribute to better flexibility.
- Low attenuation - 20 to 50% lower attenuation.
- Low signal delay - typically about 1.15 nanoseconds per foot of length.
- High corona initiation voltage - high power handling capabilities at high frequency without corona loss.
- High cut-off frequency -
- Lower capacitance - 20% less capacitance than other insulating material at the same impedance.
- Superior thermal expansion characteristics - less change in impedance and conductor breakage due to the pliable nature of porous material.

Because of the nonhomogeneous and complex construction of a shielded cable - with large and unpredictable friction and hysteresis - it is too difficult, if not impossible, to analyze its mechanical properties such as spring rate and hysteresis. Therefore, for the purpose of sizing the mechanical parameters, some sample cables have been obtained and their physical properties have been measured, although in a crude manner.

Figure 4-9 shows the actual test data of the three coaxial cables measured at room temperature. Even though Astroflex 32000 has the most attractive mechanical characteristic among the three, the superior electrical characteristics of GMCA-190 may be an overwhelming factor in coaxial cable selection.

Figure 4-10 shows that the GMCA coax cable spring constant did not vary much from 40°F to 130°F, but its hysteresis torque increased considerably as the temperature dropped from 70°F to 40°F.



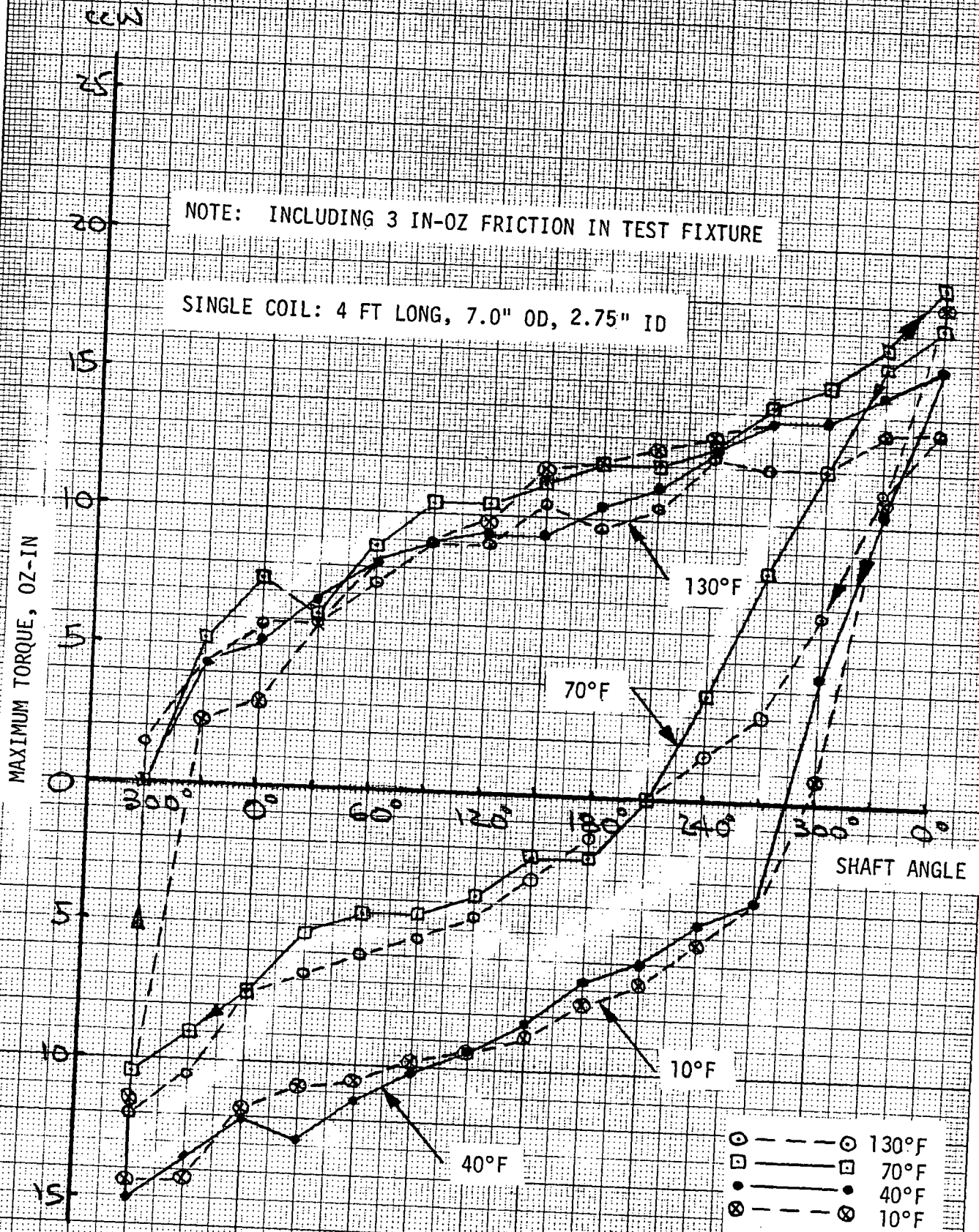
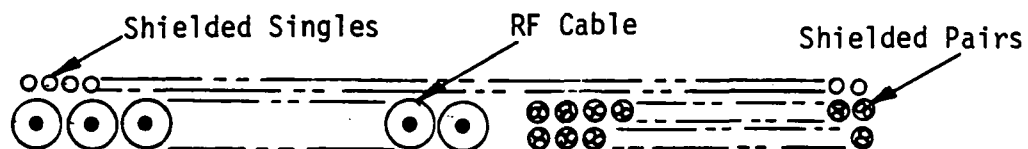


FIGURE 4.10 TEMPERATURE EFFECT ON GMCA CABLE TORQUE

Torque levels of the other two ribbon cables are plotted in Figure 4-11. Due to its thin cross-section and shield construction, the ribbon cables have much lower torque than the coaxial cable despite the large number of conductors.

Cross-section of the cable wrap design is illustrated below:



All the cables are secured at the shaft end. At the housing end (outside diameter), however, only the single shielded wire-ribbon is secured while the other ribbons are allowed to slide, so as to accommodate any change in cable length due to difference in wrap radius.

Based on the preliminary investigations, the projected cable wrap characteristics for the recommended design are summarized in Table 4-8. It can be seen that the worst cable wrap torque of 17 in-lb is well below the ADA's running torque of 33 in-lb at 4°/sec and stall torque of 188 in-lb.

4.5 Thermal Considerations

4.5.1 Design Criteria

The objective of the ADA thermal design is to maintain a reasonable temperature range for the temperature sensitive components while either operating in eclipse or exposed to direct solar radiation. Based on the known characteristics of the ADA components, the operating temperature limits are conservatively set as follows:

Low Limits:

- 0°F for ADA housing - the viscosity of lubricant for both the motor and gimbal bearings increases rapidly with decreasing temperature. In the case of high slew rate, the stepper motor bearing drag must be kept low. For instance, the drag at 0°F is 10 times that at 75°F but is only 1/10 of that at -50°F.

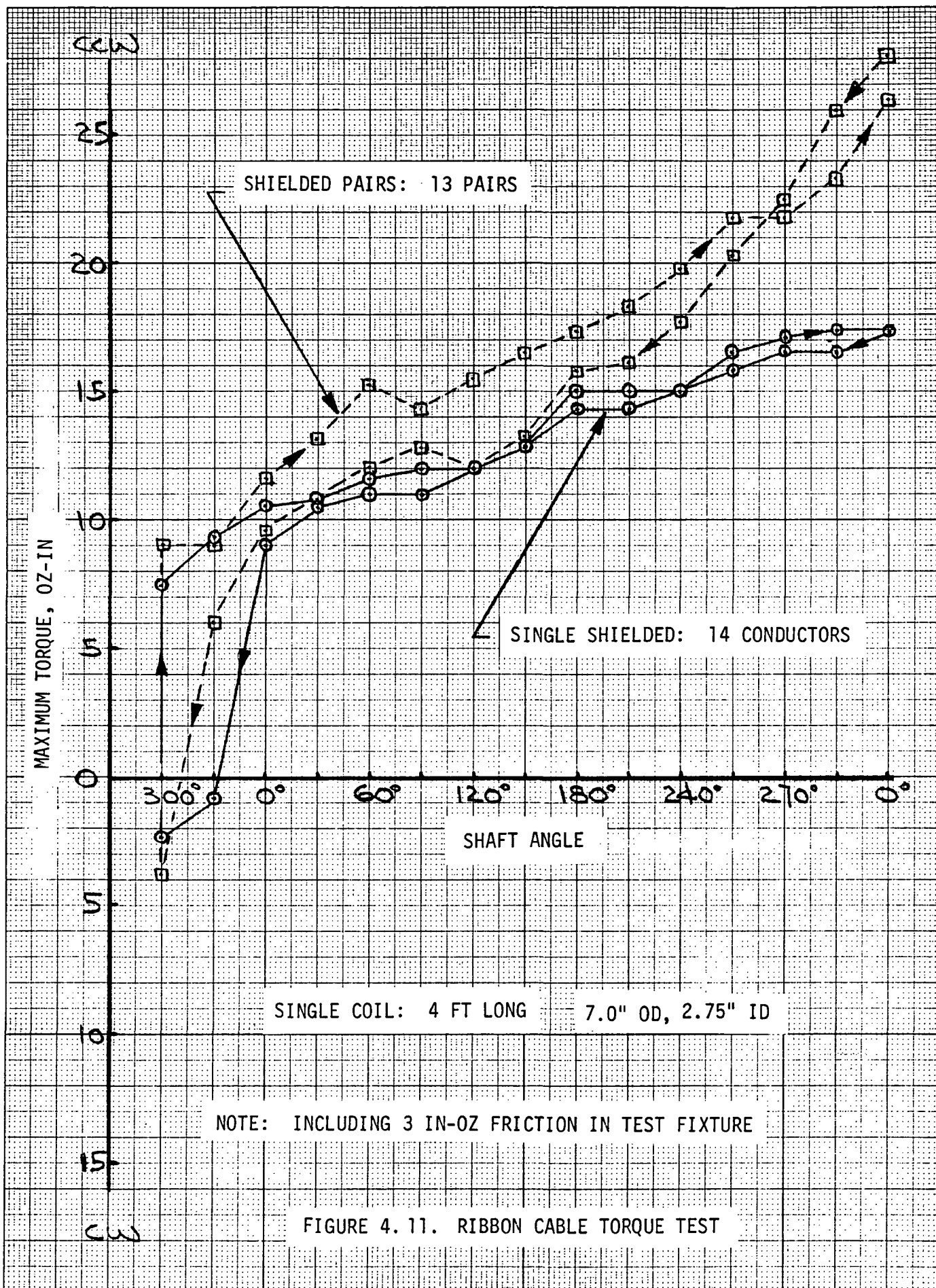


TABLE 4-8. PROJECTED CABLE WRAP CHARACTERISTICS

Specifics	Coaxial Cable	Ribbon Cable		Total
		Single Shielded	Shielded Pair	
Manufacturer	— W. L.	Gore and Associates	—	
Part No. (tested article)	GMCA	A03B060/28	A04C030/20	
Test Data:				
Conductor Size, AWG	16/19	26/7	24/19	
Shielding type	Copper braid	Served wire	Al-kapton tape	
No. of conductors	1	14	13 prs	
Spring rate, in-oz/deg	0.028	0.021	0.040	
Hysteresis & friction, in-oz max	17	7	9	
Weight, lb/ft	0.029	0.100	0.09	
Projected Cable Wrap:				
Conductor size, AWG	16/19	26/19	26/19	
Shielding type	Copper braid	Served wire	Al-kapton tape	
No. of conductors	7	31	20 prs	
Spring rate, in-oz/deg	0.20	0.05	0.06	0.0194 in-lb/deg
Hysteresis & friction, in-oz max	119	16	14	9.3 in-lb
Weight, lbs (4 ft)	0.8	0.09	0.5	2.2 lb/axis

- 40°F for cable wrap assembly - the cable wrap torque reflected to the ADA and the strain generated within each wire are inversely proportional to the cable temperature. Considering the large angle of excursion and long cyclical life required, it is desirable to maintain the cable temperature on the warm side. Lab tests have indicated that the cable torque is not appreciably increased at 40°F. (See Figure 4-10.)

High Limits:

- 120°F for ADA housing - since the evaporation rate of bearing lubricant increases with temperature, it is important to keep the bearing temperature relatively low in a direct sunlight environment.

Lab test data indicates that NPT-4 evaporation rate at 170°F and 3×10^{-6} Torr is 10 times higher than that at 130°F.

- 145°F for cable wrap assembly - this is an arbitrary limit because the cables do have a continuous-use temperature limit in excess of 300°F.

4.5.2 Design Approach

The basic thermal design approach is to isolate the ADA from external environmental effects, including the RF compartment and the deployment boom to which the ADA is attached. Since both the RF compartment and the boom have a wider temperature variation than what is allowed the ADA, it is necessary to install isolation pads (high thermal resistance) at the mounting interface so that the ADA temperature is not unduly affected by the boom or RF compartment. In order to minimize heat loss during eclipse and to reduce solar heating during sunlight portion of the orbit, the entire antenna drive assembly is covered with form-fitting multilayer insulation blankets.

In the event that internal heating is needed in the cold environment or during warmup subsequent to a long period of inactivity, a heater with minimum power consumption can be considered. As to the heater controls, a simple thermostat with wide close/open tolerance should suffice since a precision control is not required. Because of the low cost and weight in thermostatically-controlled heater design, redundancy can be provided without affecting the overall cost and weight.

4.5.3 Results of Analysis

Steady-state analysis has confirmed that thermal blanket and thermal isolation are required as indicated in the design approach (4.5.2) in order to meet the design criteria (4.5.1). The results of various operations under certain assumed conditions in the cold and hot environments are tabulated in Tables 4-9 and 4-10, respectively. Conclusions of the preliminary analysis are summarized below:

- Thermal insulation - In order to minimize both solar heating in sunlight and heat loss in eclipse, a 10-layer aluminized Kapton insulation over the ADA is found necessary.
- Thermal isolation from boom - The worst condition for ADA/boom interface is heat loss to the boom in eclipse. With a thermal resistance value of 67°F/watt in the isolation spacer design, the difference in heater power requirements between hard mounting and isolated mounting is approximately 3.5 watts, shown in Figure 4-12. Detail comparison between the two cases can be found in Table 4-9.
- Thermal isolation from RF compartment - In order to minimize the thermal dependency between ADA and RF compartment, the analysis has found that a thermal resistance of 45°F/watt for ADA/RF compartment interface can satisfy both cold and hot orbital conditions. (Cold Orbit is defined as both the boom and the ADA not being exposed to direct sunlight; Hot Orbit is defined as both the boom and the ADA receiving solar radiation, albedo, and earth IR heating.)

TABLE 4-9. HEATER SIZING STUDY SUMMARY

DESCRIPTION		ELEVATION DRIVE UNIT						AZIMUTH DRIVE UNIT						BOOM	RF COM- PARTMENT	THERMAL "ISOLATION" CONDUCTANCE (WATT/F) BETWEEN ADA AND:	
Mode	Total Heater Power (Watts)	Cable Wrap Housing		Main Housing		Cable		Cable Wrap Housing		Main Housing		Cable				°F	°F
1) Non-operating	0.0	-8	0	-13	0	-1	0	-51	0	-47	-53	0	-66	30	.015	.022	
2) Non-operating	4.0	43	1.2	33	0	37/41	0	47	2.8	32/42	21	0	-65	30	.015	.022	
3) Operating	2.5	54	0	53	0	56	0	47	2.5	35/44	25	0	-65	83	.015	.022	
4) Non-operating	0.0	-13	0	-19	0	-5	0	-65	0	-57	-69	0	-66	30	2.2	.022	
5) Non-operating	6.2	45	1.4	31	0	38/42	0	47	4.8	29/41	-15	0	-61	30	2.2	.022	
6) Operating	4.2	50	0	46	0	52	0	47	4.2	31/42	-13	0	-61	83	2.2	.022	
7) Non-operating	7.4	45	1.4	33	0	38/42	0	47	3.8	30/41	4	2.2	-59	30	2.2	.022	
8) Operating	5.6	51	0	48	0	56	0	47	3.6	32/43	4	2.0	-59	83	2.2	.022	

ORBITAL ENVIRONMENT: COLD ORBIT - NO SOLAR HEATING ON ADA OR BOOM.

BOOM: EMISSIVITY = .30

MULTILAYER INSULATION: SOLAR ABSORPTIVITY = .40 EMISSIVITY = .49

EFFECTIVE CONDUCTANCE (ϵ^*) BETWEEN INNER AND OUTER INSULATION LAYERS = .04

NOTE: THIS DATA IS BASED ON STEADY STATE ANALYSIS USING ORBITAL AVERAGE CONDITIONS FOR THE EXTERNAL ENVIRONMENT. THE ACTUAL PERTURBATIONS ON THESE TEMPERATURES DUE TO ACTUAL VARYING ORBITAL CONDITIONS IS MINOR (APPROXIMATELY 8°F).

TABLE 4-10. ANTENNA GIMBAL ASSEMBLY OPERATION DURING HOT ORBIT

DESCRIPTION		ELEVATION DRIVE UNIT						AZIMUTH DRIVE UNIT						BOOM	RF COM- PARTMENT	THERMAL "ISOLATION" CONDUCTANCE (WATT/F) BETWEEN ADA AND:	
Mode	Total Heater Power (Watts)	Cable Wrap Housing		Main Housing		Cable		Cable Wrap Housing		Main Housing		Cable		°F	°F	Boom	RF Compartment
		°F	Watts	°F	Watts	°F	Watts	°F	Watts	°F	Watts	°F	Watts				
1) Operating	0.0	103	0	99	111	0	0	98	0	99	105	0	108	83		.015	.022
2) Non-operating	4.0	149	1.2	140	156	0	0	185	2.8	182	169	0	108	83		.015	.022
3) Operating	2.5	119	0	115	133	0	0	170	2.5	165	157	0	108	83		.015	.022
4) Operating	0.0	99	0	96	106	0	0	85	0	87	88	0	108	83		2.2	.022
5) Non-operating	7.4	151	1.4	142	155	0	0	184	3.8	181	151	2.2	110	83		2.2	.022
6) Operating	5.6	119	0	115	132	0	0	175	3.6	171	145	2.0	110	83		2.2	.022

ORBITAL ENVIRONMENT: HOT ORBIT - SOLAR, ALBEDO, AND EARTH IR HEATING ON MOTORS AND BOOM

BOOM: SOLAR ABSORPTIVITY = .46 EMISSIVITY = .30

MULTILAYER INSULATION: SOLAR ABSORPTIVITY = .40 EMISSIVITY = .49

EFFECTIVE CONDUCTANCE (ϵ^*) BETWEEN INNER AND OUTER INSULATION LAYERS = .02

NOTE: THIS DATA IS BASED ON STEADY STATE ANALYSIS USING ORBITAL AVERAGE CONDITIONS FOR THE EXTERNAL ENVIRONMENT. THE ACTUAL PERTURBATIONS ON THESE TEMPERATURES DUE TO ACTUAL VARYING ORBITAL CONDITIONS IS MINOR (APPROXIMATELY 8°F).

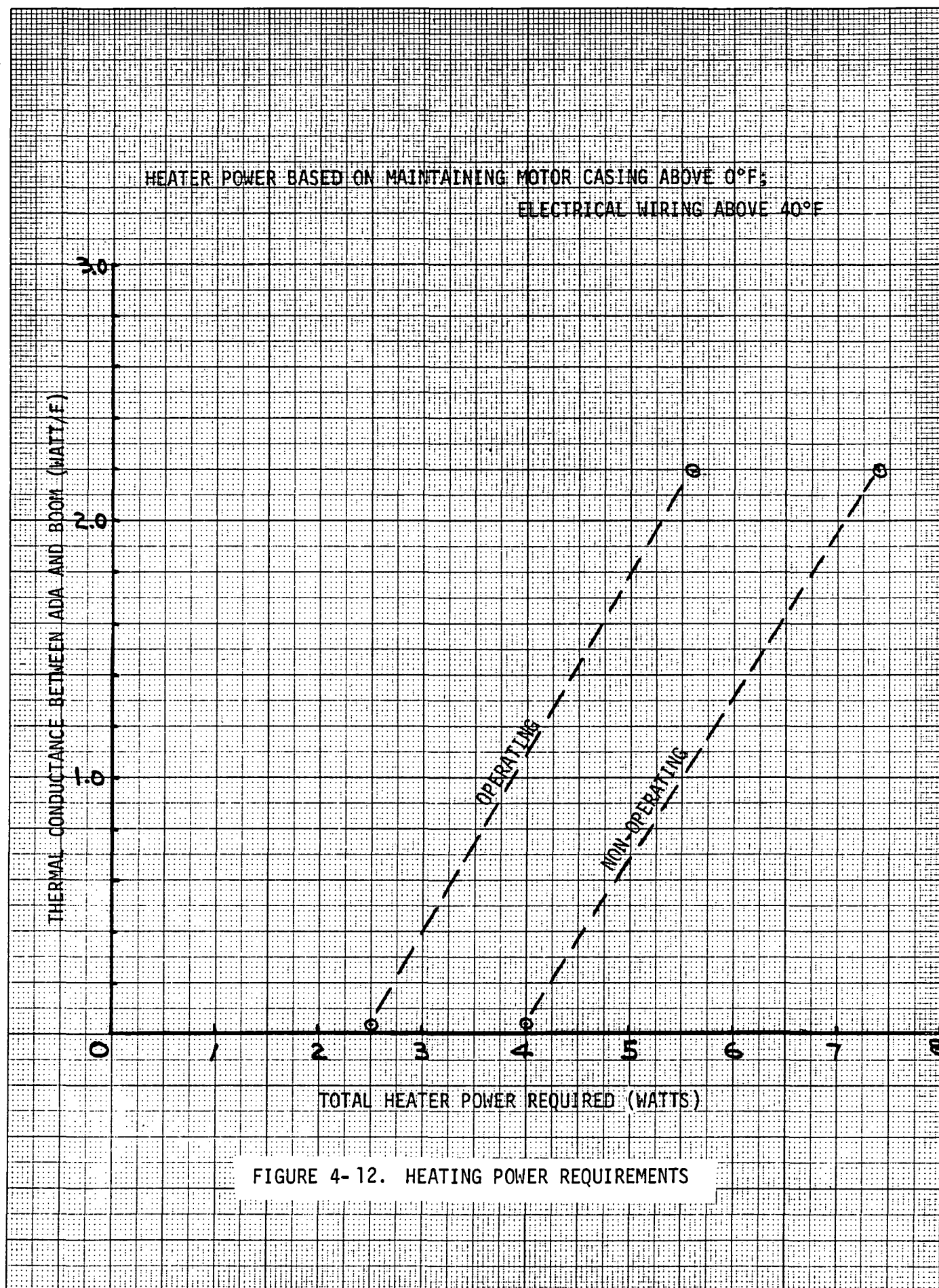


FIGURE 4-12. HEATING POWER REQUIREMENTS

- Heater requirements - With the prescribed thermal insulation and isolations mentioned above, a 2.5 watt heater installed on the azimuth drive's cable wrap housing can maintain a satisfactory operating temperature for the ADA in the cold orbit as seen in Mode 3, Table 4-9. However, with this heater, the warm-up time required from a cold-soak temperature of -60°F is approximately 25 hours, as seen in Figures 4-13, 4-14, and 4-16.

For fast warm-up, two alternatives are recommended: (1) to leave the 2.5-watt heater on during the period of inactivity, similar to Mode 2 of Table 4-8, or (2) to add an auxiliary heater which can be sized from Figure 4.8.

- Thermostat - In hot orbit, the ADA operating temperature is within the desired range even without heater, as evidenced in Mode 1 of Table 4-9. However, the ADA temperature becomes too high with the 2.5 watt heater on; see Mode 2 of Table 4-9. Therefore, a thermostat is required to cut off the heater at a preset temperature level.

4.5.4 Design Implementation

The thermal blanket is made of 10 layers of thin gauge (50 gauge) aluminized Kapton sheets. The selection of Kapton over Mylar is based on its better stability when exposed to space environment for long periods of time. The outermost layer of insulation is applied with its aluminized surface inside because the bare Kapton surface has a lower α/ϵ ratio. Although the aluminized surface has a much lower emissivity, its high α/ϵ ratio would generate a temperature exceeding the recommended limit (400-500°F) for Kapton, when exposed to the sun. Since the effective conductance between the Kapton layers varies with their contacting surface area and the method of mounting, a range from .02 to .04 can be expected. For the purpose of analysis, the high number is used to size the heater requirement for cold environment operation, and the low number is used to compute the maximum ADA temperature in the hot environment.

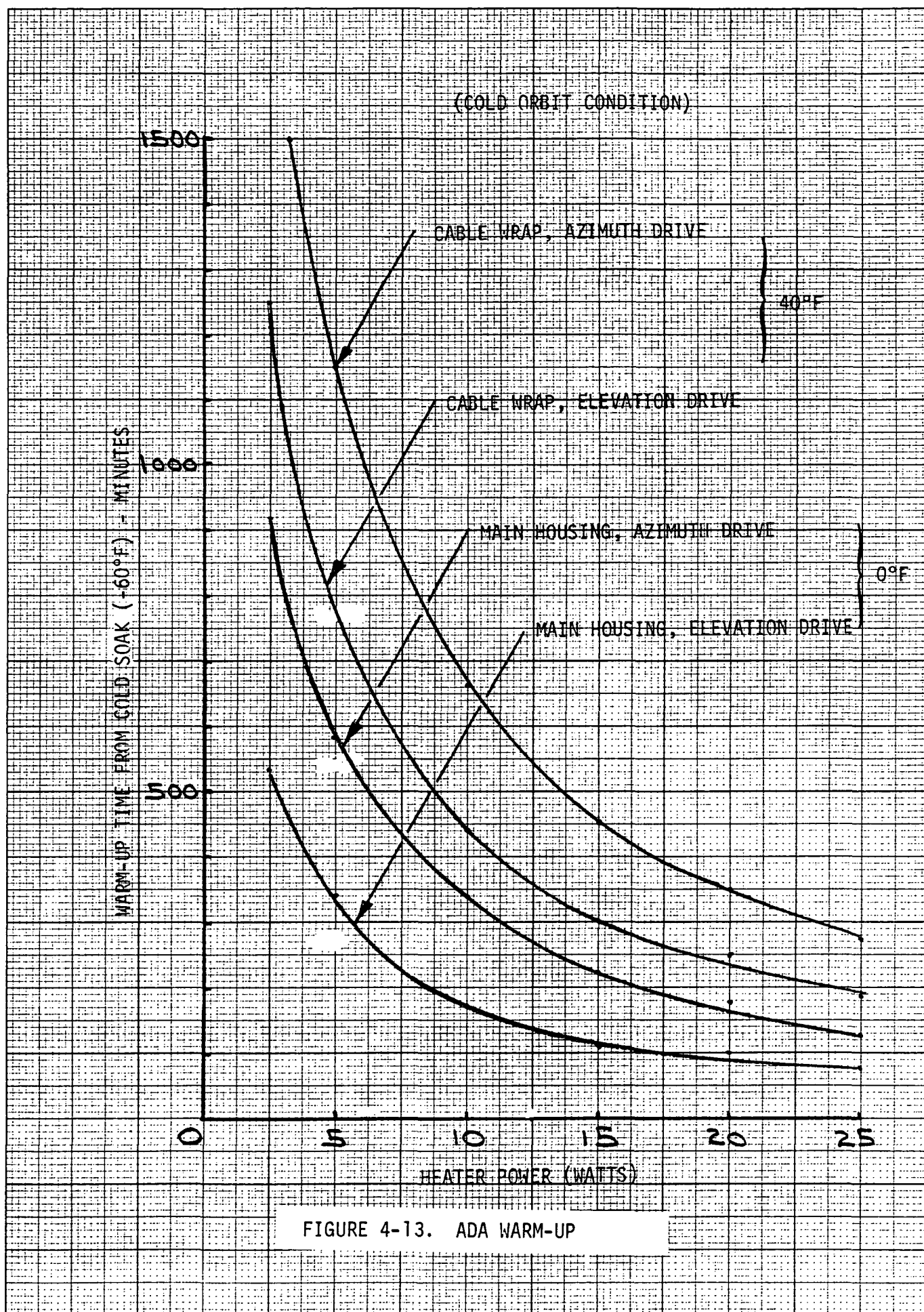
As seen from Tables 4-9 and 4-10, the boom temperature varies from -65°F in cold orbit to +110°F in hot orbit because it is exposed directly to the external environment. To minimize its impact to the ADA temperature, spacers made of high thermal resistance material such as laminated glass can be used at the ADA's mounting interface with the boom and the RF compartment. The values generated in Tables 4-9 and 4-10 are based on using 1/2 inch thick spacers between ADA and boom, and 1/4 inch between ADA and RF compartment.

Although the boom design is not a part of this study, its thermal property has significant influence to the ADA temperature and the cable harness running along it. Therefore, it is suggested that the boom should either be insulated with a thermal blanket or have a low emissivity finish with low α/ϵ ratio. For the purpose of analysis in this study, the following characteristics of the boom have been assumed:

- Diameter - 8 inches
- Material - aluminum alloy
- Finish - roughened aluminum surface with
solar absorptivity $\alpha = 0.46$
infrared emissivity $\epsilon = 0.30$

The heater recommended for the ADA is a strip heater - heating foil laminated between Kapton films - measuring 0.5" wide x 8.0" long. It is bounded onto the azimuth drive cable wrap housing. Heat distribution to the azimuth stepper motor and gimbal bearings is through conduction, whereas the cable wrap is warmed up by both conduction through the electrical wires and radiation from the cable wrap housing. The elevation module components are mostly warmed up by the heat leaked-in from the RF compartment. As mentioned previously, for faster warmup, a 1.2 watt heater added to the elevation axis cable wrap housing can reduce the warmup time by 40%.

To prevent overheating, a thermostat mounted on the adapter ring (between the two drive modules) will automatically cut off the heater power at a preset temperature. It will also automatically turn on the heater when the ADA drops below a preset temperature unless the heater power is shut off upon command at the power source for a long period of dormancy and power conservation.



COLD ORBIT-UPPER DRIVE TEMPERATURES (2.5 WATT HEATER POWER)

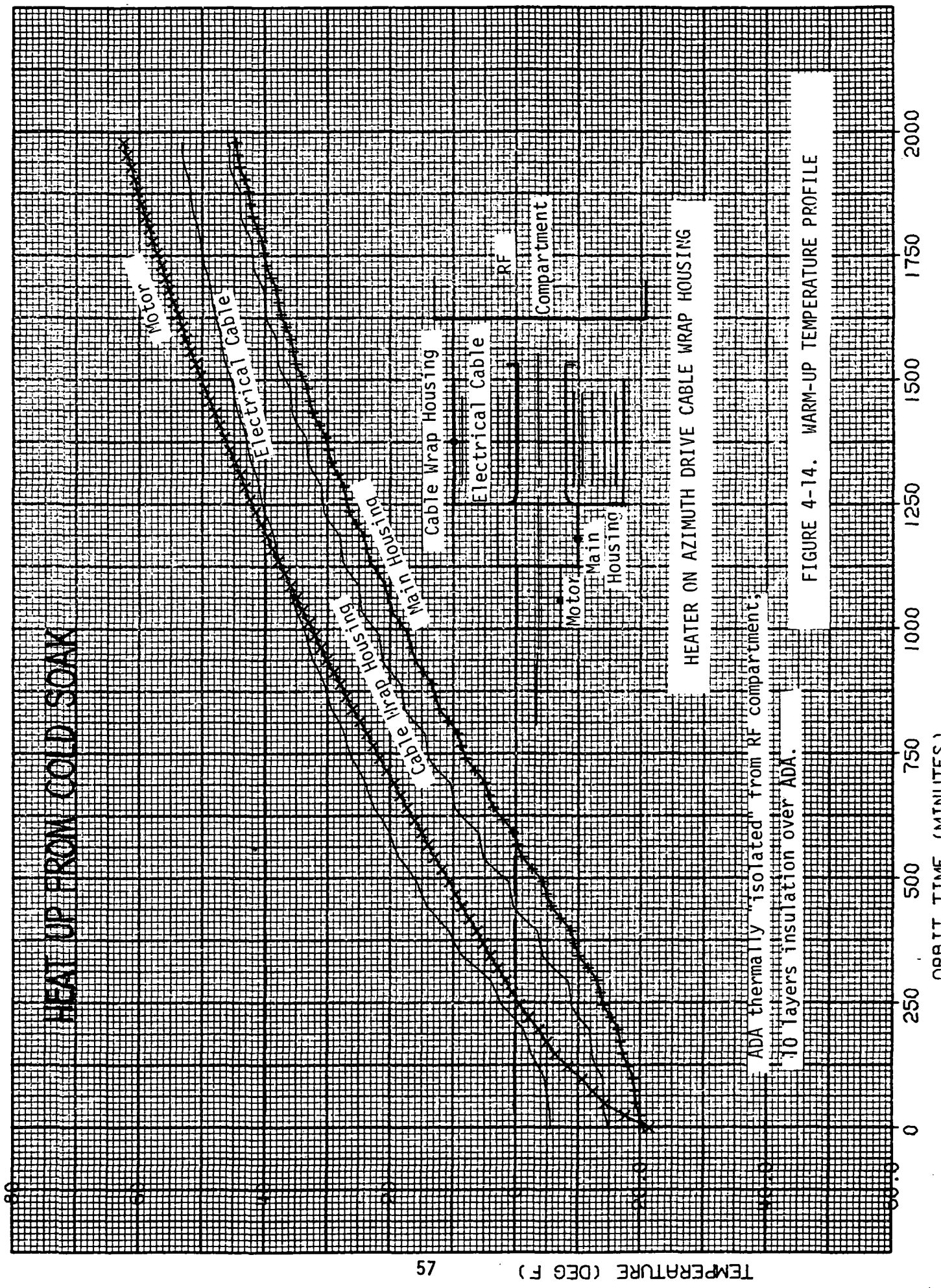
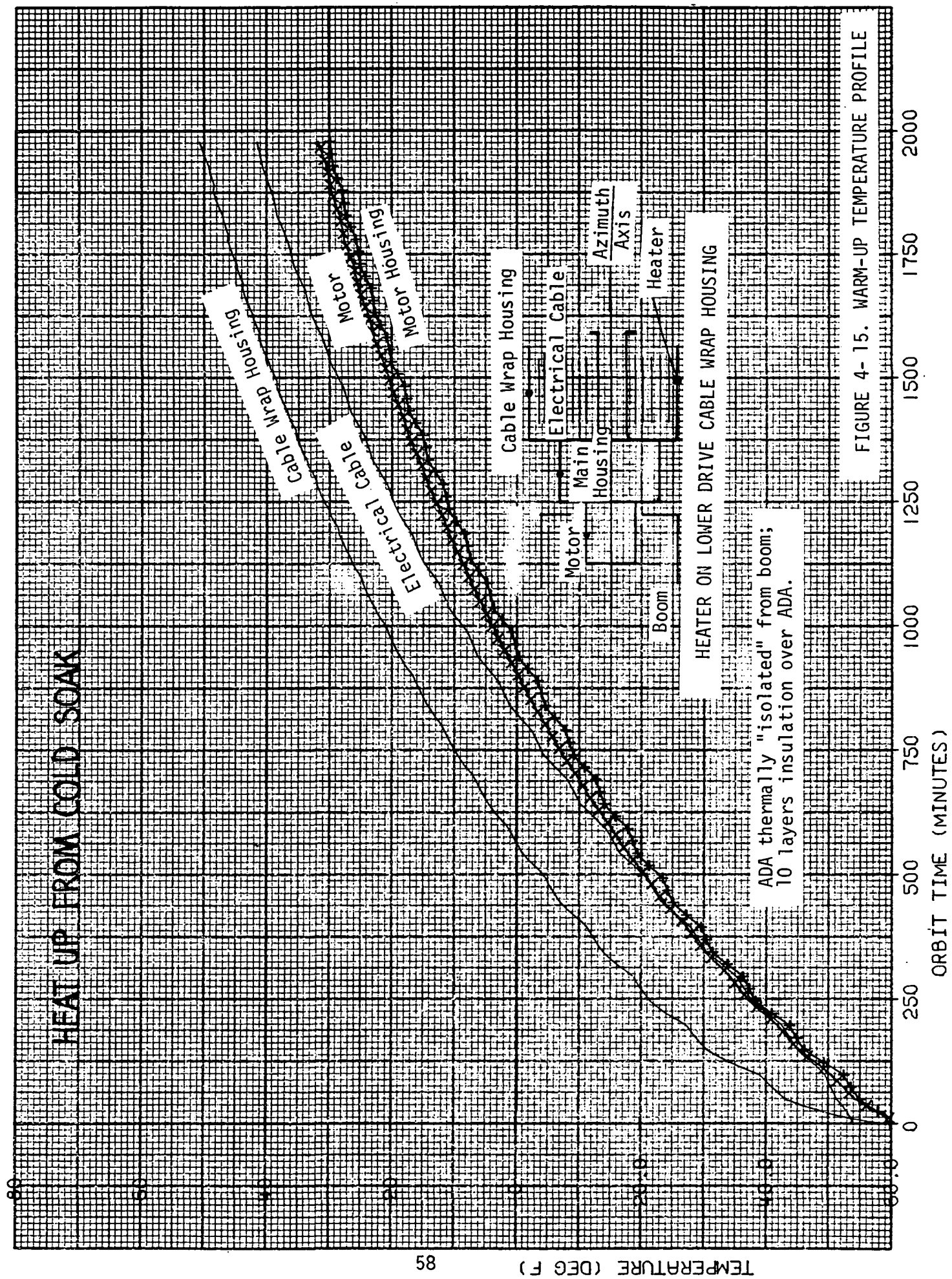


FIGURE 4-14. WARM-UP TEMPERATURE PROFILE

COLD ORBIT-LOWER DRIVE TEMPERATURES (2.5 WATT HEATER POWER)



5.0 DRIVE ELECTRONICS

5.1 General Description

The Gimbal Control Electronics (GCE) for the recommended ADA, shown in Figure 5.1, performs the following functions:

- Accepts antenna gimbal position commands via the data handling module and converts them to drive pulses for the stepper motors which drive the elevation and azimuth gimbals to the commanded positions.
- Accepts analog autotrack signals and provides pulses to the gimbal stepper motors for azimuth/elevation autotracking.
- Converts azimuth and elevation gimbal resolver outputs to 12 bit digital data for telemetry and for feedback in the position mode.
- Provides dc to dc power conversion for all internal secondary power requirements.

The GCE consists of identical circuitry for both the azimuth and elevation channels, and it is divided into the following six sections:

- 1) Command Input and Control Logic
- 2) Motor Drive and Sequence Logic
- 3) Gimbal Resolver Processing and Telemetry
- 4) Clock, Clock-Countdown and Resolver Excitation
- 5) Autotrack Thresholding and Mode Switching
- 6) Power Input and Converter

Characteristics of the GCE are estimated as follows:

Size:	10 x 9 x 3 inches
Weight:	6 lbs
Power:	6 watts (while slewing both motors)

5.2 Command Input and Control Logic

Input commands (to the GCE) are received in the form of 16 bit serial data words from the Remote Unit (RMU). Three signals are received from the RMU to accomplish transmission; i.e., a Gates Clock, a Serial Enable, and a Data Line. Twelve bits are used for gimbal position data; one bit is used to identify the axis (azimuth or elevation) and another bit is used to command the mode (position or autotrack). The remaining bits are unused.

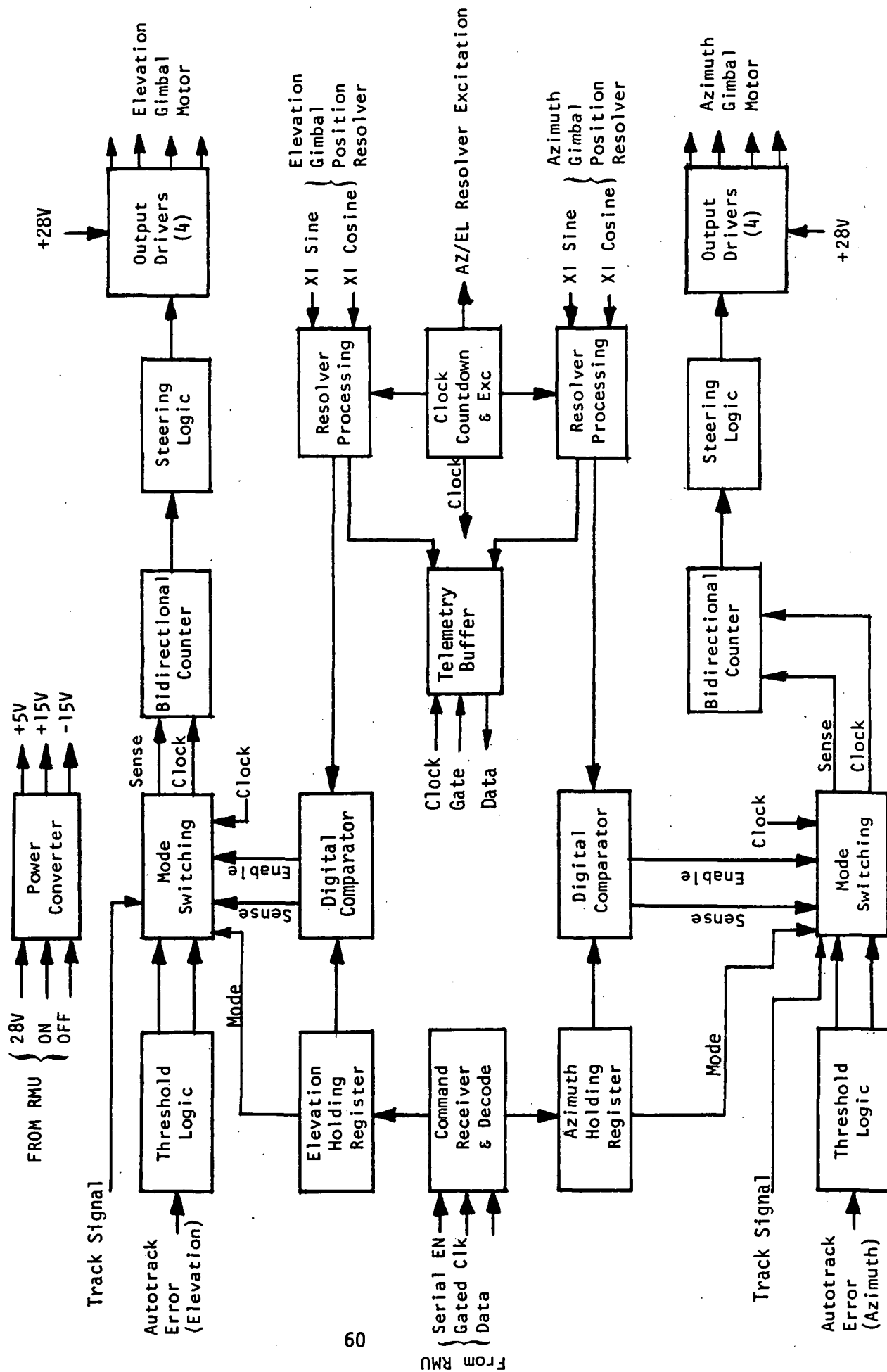
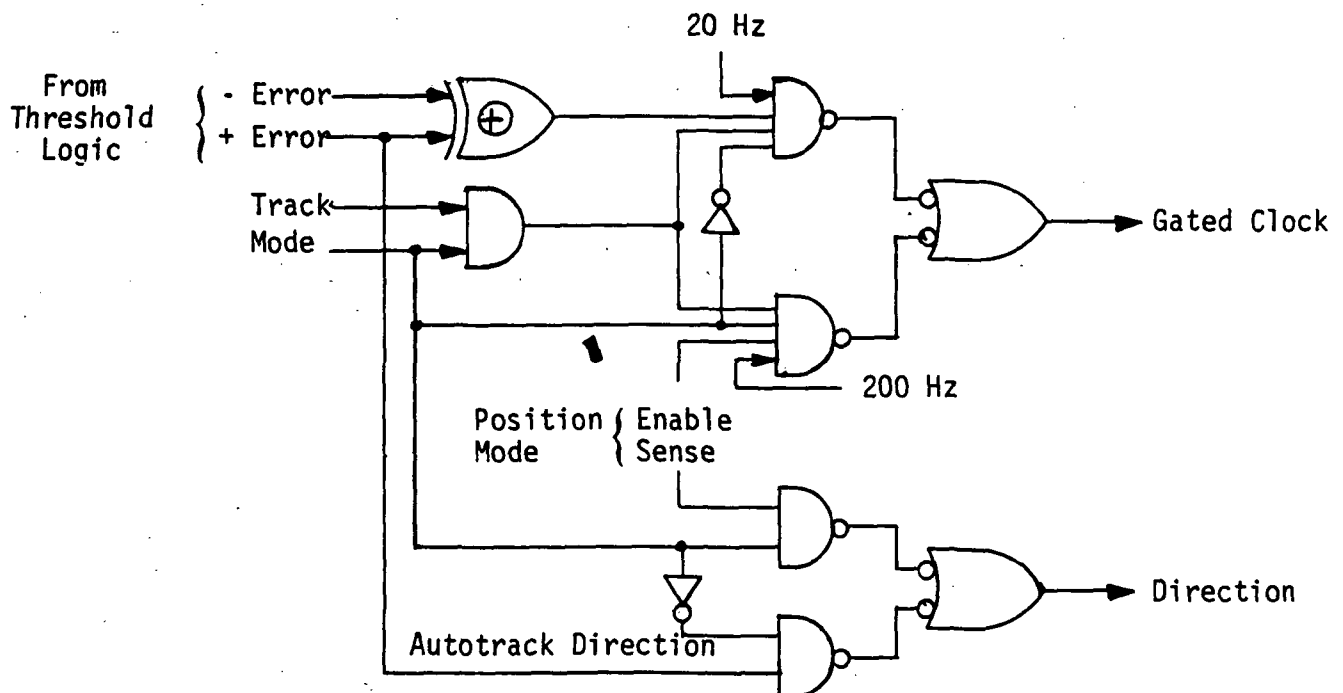


FIGURE 5-1. GIMBAL CONTROL ELECTRONICS

As shown in Figure 5-1, the serial data is clocked into a 16-bit serial shift register in the GCE. When the Serial Enable signal falls to a logic "0", a trailing edge detector generates an execute pulse. The execute pulses and the axis identification bit are used to load the data into either the azimuth or elevation holding registers. In the position mode, the 12-bit data is compared with the 12-bit resolver data in a digital comparator. When the two words are different, the comparator output provides a clock enable. The comparator also provides a direction sense line which is a result of a "greater than" or "less than" comparison. These signals, via the mode switching circuitry, enable stepper motor pulses at 200 Hz, until the gimbal is driven to the commanded angle. Gimbal movement ceases when the command word and the resolver data word are equal.

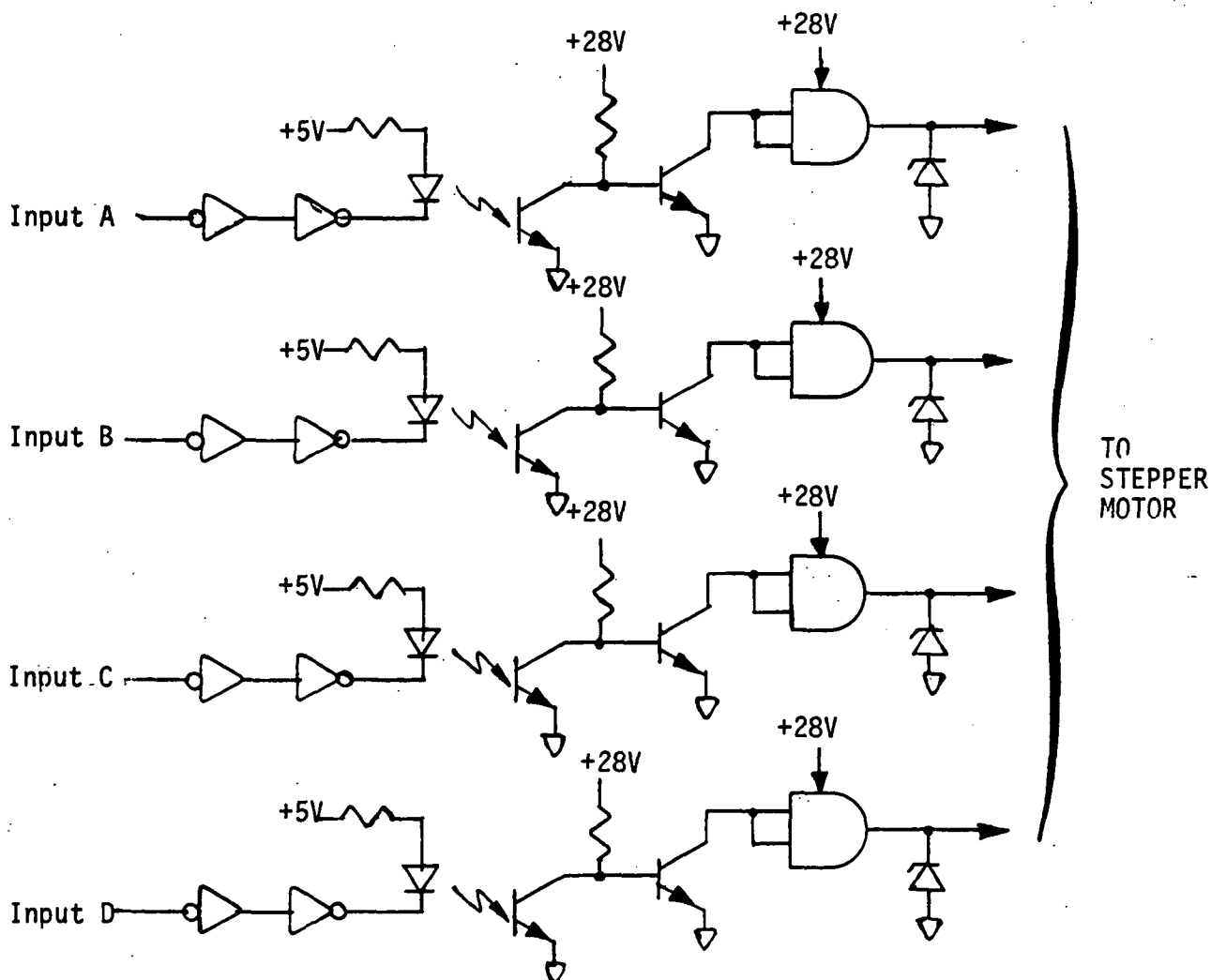
The mode bit specifies either the above position mode or the autotrack mode. In the autotrack mode, the position data and resolver data are not used in controlling the stepper motors, but instead, the autotrack receiver outputs are processed to generate the clock enable and sense signals. The clock frequency for autotrack mode is 20 Hz, thus providing a 0.25 degree/second tracking. The schematic for the mode switching circuit is shown below:



5.3 Motor Drive and Sequence Logic

The motor drive output circuit, as shown in the sketch below, is comprised of a four section hybrid power driver that interfaces with T^2L logic via optical couplers. The drivers are capable of driving loads up to 35 volts at current levels in excess of 0.5 amperes. The optical couplers are employed to meet primary/secondary ground isolation requirements.

The sequence logic is comprised of a conventional bi-directional gray-code ring-counter. The direction of count is controlled by the direction line from the mode switching circuit. The four possible output states are decoded into A, B, C, D conditions by the steering logic for sequentially turning on and off the power output drivers.



5.4 Gimbal Resolver Processing and Telemetry

The antenna gimbal angles are encoded from single speed resolver outputs for both azimuth and elevation. The processing electronics is identical for both axes and provides 12 bits of digital angle data for each. This results in an angle quantization of 0.09 degrees. The basic technique used to convert resolver shaft angle data into digital form is "double angle" encoding, which provides amplitude to phase conversion of the resolver sine and cosine outputs. After conversion to amplitude phase modulated sinusoids, the zero crossings are detected using voltage comparators. This results in squarewaves whose electrical phase difference is two times the shaft angle θ for the single speed resolver. The digital equivalent of angle is then generated by accumulating the number of high frequency clock pulses which occur between the falling edges of the phase-shifted squarewaves. After this count is accumulated in a ripple counter, it is loaded into two parallel-to-serial shift registers. One is used in the computation required in the position mode and the other is for the telemetry buffer which is sampled by the RMU.

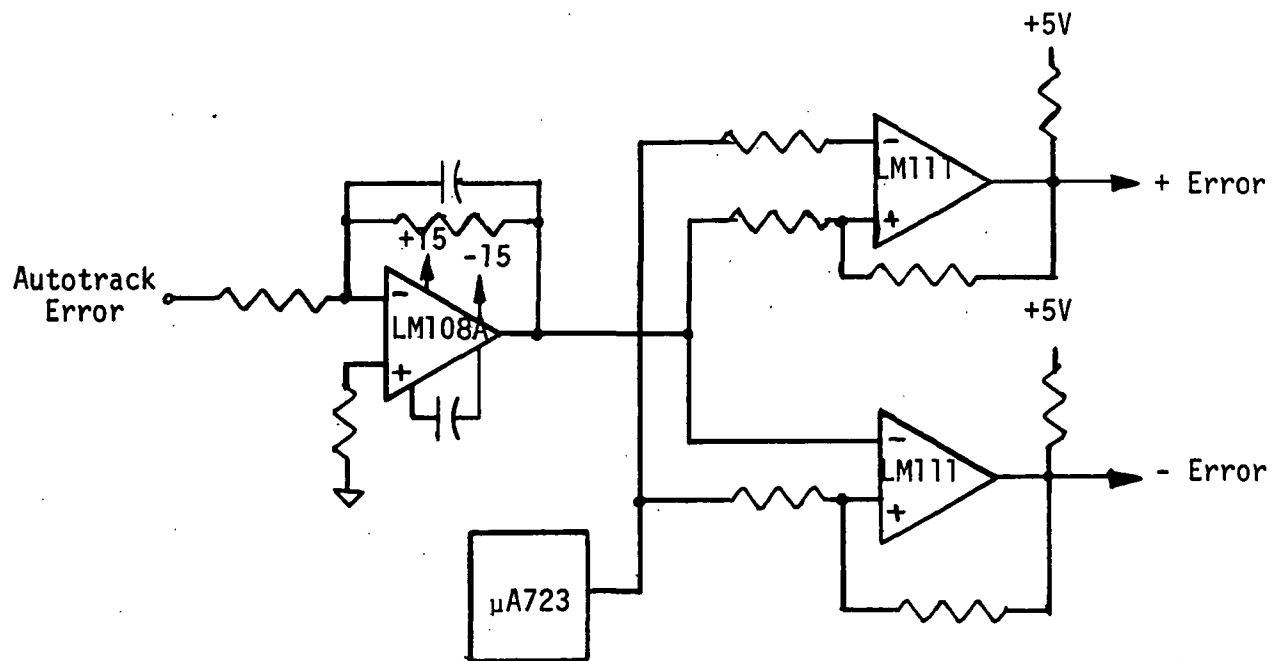
5.5 Clock, Clock Countdown, and Resolver Excitation

The GCE clock is a quartz crystal oscillator operating at 2.09 MHz which provides the basic excitation for both axes. A series of binary divisions is made using 4-bit ripple counters to obtain the 1024 Hz fundamental resolver excitation frequency, as well as providing frequencies for synchronization and control.

The precision 1.024 KHz digital clock is used to drive a buffer which feeds a sharp cutoff low-pass filter. This filter removes all but the fundamental component of the squarewave. The sinusoidal output from the filter is scaled and power amplified to provide an 8 volt peak, 1.024 KHz sinusoidal excitation for both gimbal resolvers.

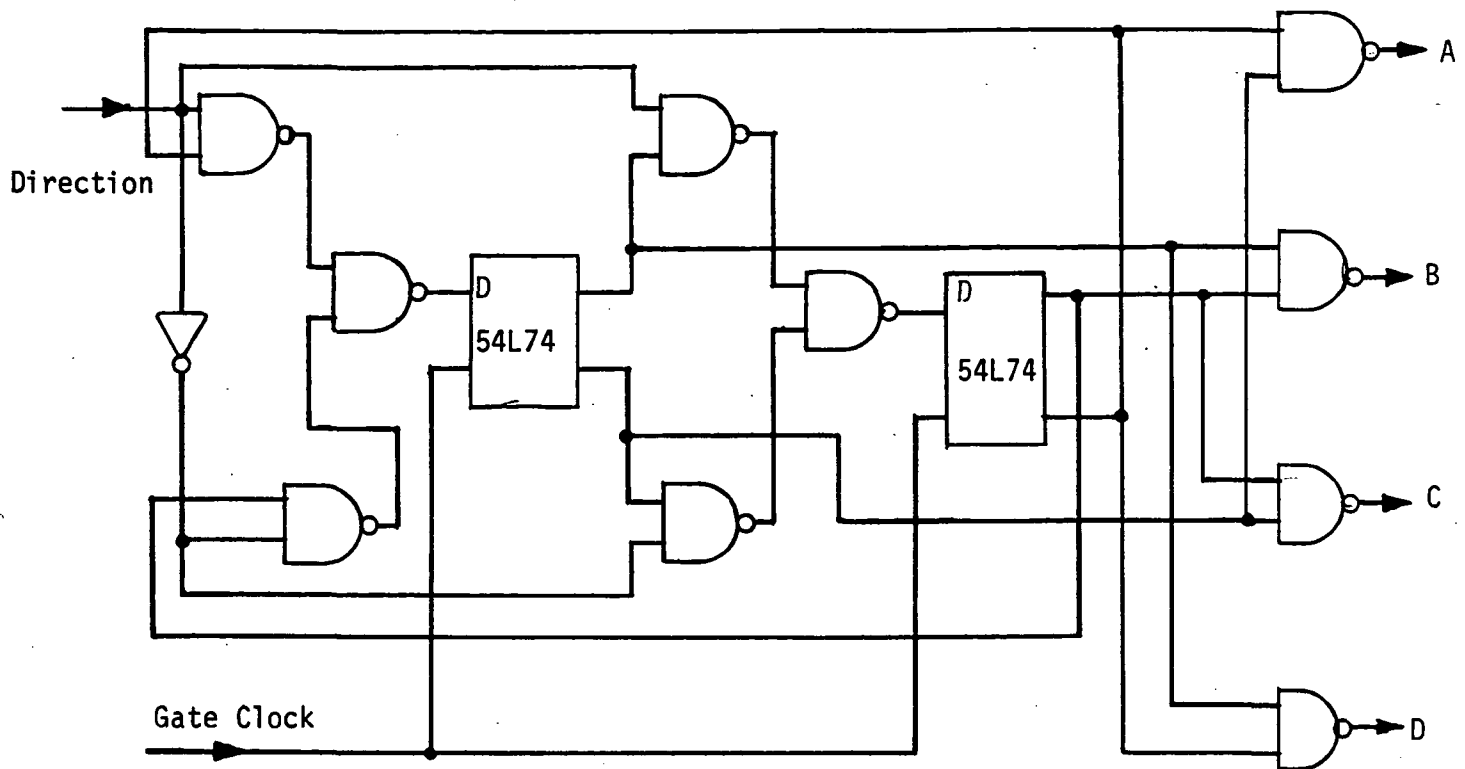
5.6 Autotrack Thresholding and Mode Switching

Bipolar analog error signals are received by the GCE from the Autotrack Receiver along with a bilevel (track) indicating valid signal presence. In the autotrack mode, no action is taken without a valid track signal. The analog signals are first filtered and then threshold-detected in LM111 threshold detectors. One threshold detector is utilized for each polarity of the analog signal. Exclusive "oring" of these detectors provides the clock enable signal for the drive channel. The thresholds are set below the resolution requirements for autotracking, but above the level which would induce hunting. The direction is derived from one of the threshold detectors.



Threshold Logic

The mode switching section is a set of combinational logic which simply controls the clock, clock enable, and motor direction as a function of mode and track signal status.



Didirectional Counter and Steering Logic

5.7 Power Input and Converter

The bus power input to the GCE is brought in through two 5-ampere feed-through type high frequency line filters and is filtered further by a low pass second-order network that rolls off at approximately 800 Hz. The filtered bus is then switched to the power converter and motor driver outputs by a half-crystal-can magnetically-latched relay. The relay coils are driven from the RMU by 50 msec, 28 volt pulses for the GCE ON-OFF control.

The power converter utilizes a conventional series type loss regulator to control the input voltage to the dc-to-dc converter section to +20.0 volts. The 20 volts is then converted to ac by a pair of 2N2851 transistors operating into a nonsaturating inverter transformer. The inverter frequency of approximately 20 KHz is controlled by the volt-second storage capability of another inductor. The secondary voltage outputs of -15, +15, and +5 volts are full wave rectified from a pair of windings of the inverter transformer.

6.0 REFERENCES

- (1) Design Study Landsat Follow-On Mission Unique Communications System, TRW Report 14897-6007-RU-00, August 1976.
- (2) Design Study for Landsat-D Attitude Control System, TRW Report 14897-6010-RU-00, February 1977.
- (3) Landsat-D Instrument Module Study, NASA/GSFC Report N77-150-61 prepared by Grumman Aerospace Company, December 1976.
- (4) Rolling Bearing Analysis, T. A. Harris, pages 292-293, J. Wiley & Sons, Incorporated, 1966.
- (5) A Fluid Mechanis Approach to the Labyrith Seal Leakage Problem, Gezavermes, Journal of Engineering of Power, April 1961.